



Review

# Health and Safety Concerns Related to CNT and Graphene Products, and Related Composites

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**Abstract:** The use of Carbon Nanotubes (CNT) and Graphene increased in the last decade and it is likely to keep increasing in the near future. The attractiveness of their properties, particularly the possibility to enhance the composites performance using a tailor made methodology, brings new materials, processes and products for highly demanding industrial applications and to the market. However, there are quite a lot of health/safety issues, as well as lack of understanding and standards to evaluate their effects. This paper starts with a general description of materials, processes and products dealing with CNT and graphene. Then, an overview of concerns related to the health and safety when handling, researching, producing and using products that include these materials is presented. It follows a risk management approach with respect to simulation and evaluation tools, and considering the consensual limits already existing for research, industry and consumers. A general discussion integrating the relevant aspects of health and safety with respect to CNT and graphene is also presented. A proactive view is presented with the intention to contribute with some guidelines on installation, maintenance, evaluation, personal protection equipment (PPE) and personnel training to deal with these carbon-based nanomaterials in research, manufacture, and use with composite materials.

**Keywords:** CNT; graphene; health; safety; risk management; composite materials

## 1. Introduction

In this century, the field of nanotechnology has risen to the forefront of research and development, standing out the carbon nanoallotropes. The specific and excellent properties of CNTs and graphene pave the way to an ever-increasing number of applications, such as medical devices and drugs, energy, environment, biology, aerospace, aeronautics, automotive, sports, electronics, solar cells, structural batteries, adhesives, composites, polymers, super capacitors, ultra-stiff materials, gas sensors, biosensors, wastewater treatment, reinforced rods, mechanical memories, coatings, and films [1–6]. In fact, they present high tensile strength and modulus, high thermal and electrical conductivities, high absorbency and aspect ratio and low weight, which means that these nanomaterials have very high specific properties. However, the health and safety implications of Engineered nanomaterials—ENM, including CNT and graphene, are far away from being understood and full of uncertainties. In fact, the high exposures are likely to cause harm to the researchers in laboratories, workers in industrial

production sites or in the waste, recycling industries, consumers, and environment [3–5,7]. Therefore, it is essential to assess the short, medium and long-term effects and potential risks [8,9].

Both academic laboratories and industries, where the work in the field of nanotechnology is very active, it is particularly important to prevent and mitigate the risks associated with the handling, producing and transforming nanomaterials by establishing laboratory procedures and guidelines to avoid unexpected and unnecessary concerns [9,10]. Decision makers, researchers, production and maintenance workers must evaluate risks and take the precautionary measures to have a safer working atmosphere [11]. Nanosafety must be considered in the development phase, covering the total life cycle, ensuring that nanotechnology may provide answers to society needs [12]. The aim of this paper is to contribute to these goals.

Starting with a brief description of materials, processes and final products that deal with CNT and graphene, the paper presents the more relevant health and safety concerns before going to the risk assessment methodologies. After a general discussion, we move to a proactive view where some guidelines will be addressed.

To develop the proposed work a holistic review was performed based on diverse bibliography concerning the health and safety issues related to CNT and graphene products, mainly on the reported literature from 2000 to 2020. The literature review was carried out using search engines, and other databases, with the following search strategy: combination of the keywords and sub-keywords; selection of the relevant articles by reading the title and abstract; and, full text reading of the selected articles. After selecting the items, a critical analysis was performed.

## 2. State of the Art Review

The main aim of this systematic review was to evaluate briefly the state of art of the health and safety concerns related to CNT and graphene products, including composite systems with these nanomaterials.

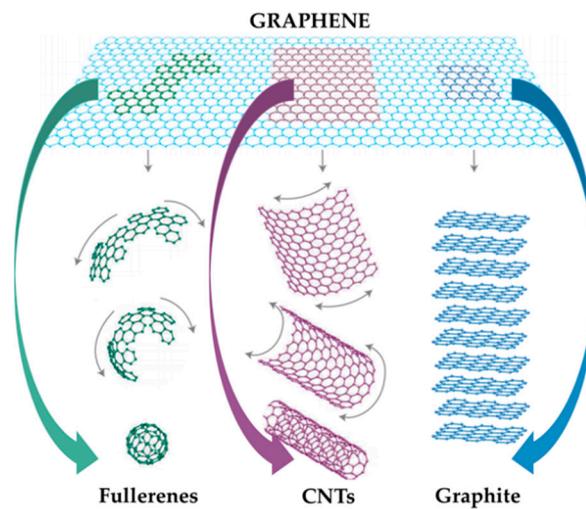
Therefore, firstly in this section, the use of nanomaterials will be described, how they are produced and processed to yield a product with enhanced properties, following a systematic review related to the ENM and their applications.

Secondly, an overview of concerns related to the health and safety when handling, researching, producing and using products that include these nanoengineered materials is presented, bearing in mind exposure in occupational operations and end users practices.

At last, the risk management approaches are presented in terms of simulation and evaluation tools for research, industry and consumers' management.

### 2.1. Materials

Different types of carbon engineered nanomaterials derived from graphene (Figure 1) can be considered: fullerenes, carbon nanotubes, graphene and their derivatives [13]. They have attracted worldwide applications (energy, aeronautics, environment, biology, medicine, etc.), due to their unique properties that make them promising candidates for a wide range of applications.



**Figure 1.** Relation between graphene and other carbon allotropes, adapted from [13].

Figure 1 shows graphene as the building block of all graphitic carbon allotropes with different dimensionalities [13].

Carbon-based nanomaterials can appear with different aspects and morphologies, such as hollow tubes, ellipsoids, platelets or spheres [1]. Fullerenes, such as C<sub>60</sub>, carbon nanotubes (CNTs), carbon nanofibers (CNFs), carbon black and graphene are all included under the carbon-based nanomaterials category [14]. These are considered of particular interest as nanoreinforcements to the Carbon Fibre Reinforced Polymer (CFRP) composites community, showing the ability to improve their global performance, as can be seen in Table 1 [2].

**Table 1.** Some changes induced by the carbon nano allotropes addition to CFRP.

Type	$\phi^a$ (nm)	Content (wt. %)	Relevant Property Improvements
Carbon Nanofibres	60 to 200	2.0	+22% Flexural strength +11% Tensile strength +4% Glass transition temperature [15]
	~200	0.3	+79% Impact absorption energy +42% Inter-laminar shear strength +14% Flexural strength [16]
Multiwalled carbon nanotubes	10 to 20	0.3	+25 % Flexural strength [17]
	~10	0.5	+3% Tensile strength [18]
	30 to 50	0.3	+53% Flexural modulus [19]
Graphene	8	0.1	+11% Fracture toughness [20]
	5	0.4	+19% Tensile modulus +18% Tensile strength +19% Flexural modulus
			+15% Flexural strength [21]
	100	4	+19% Interlaminar Shear Strength +26% Flexural modulus (90°) +82% Flexural strength (90°) +4% Flexural modulus (0°) +7% Flexural strength (0°)
			+167% Electrical conductivity [22]

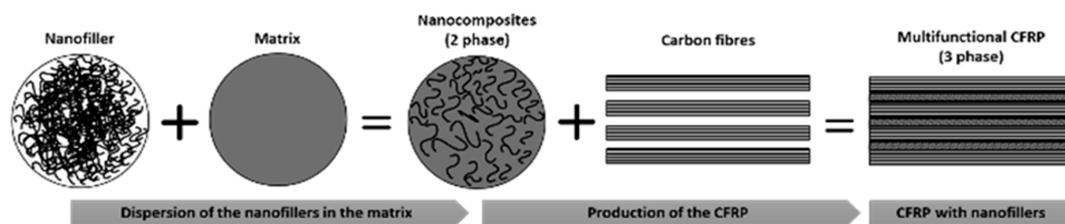
<sup>a</sup> Average diameter or length/thickness.

The Single Wall Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs) may have similar lengths, ranging from hundreds of nanometers to tenths of micrometers, although they have also different diameter ranges. The SWCNTs have typical diameters between 1 and 3 nm, whilst MWCNTs range from 10 to 200 nm. Similarly, graphene flakes present thicknesses of one carbon atom while their lateral dimensions may vary from hundreds of nanometers to hundreds of microns. From graphene to a few-layer graphene and graphite, flakes with increasing thickness are also available. The size and shape aspects of these nanoparticles should be accounted for assessing health and safety issues [1,3,11,14,23].

The CNTs and CNFs are available as liquid dispersions, dry powders or embedded in polymers as nanocomposites or CFRP composites [23]. For many applications, it is necessary to modify and functionalize the CNTs surface, aiming at ensuring a better compatibility and a stronger interface between the nanofiller and the polymeric matrix.

## 2.2. Processes

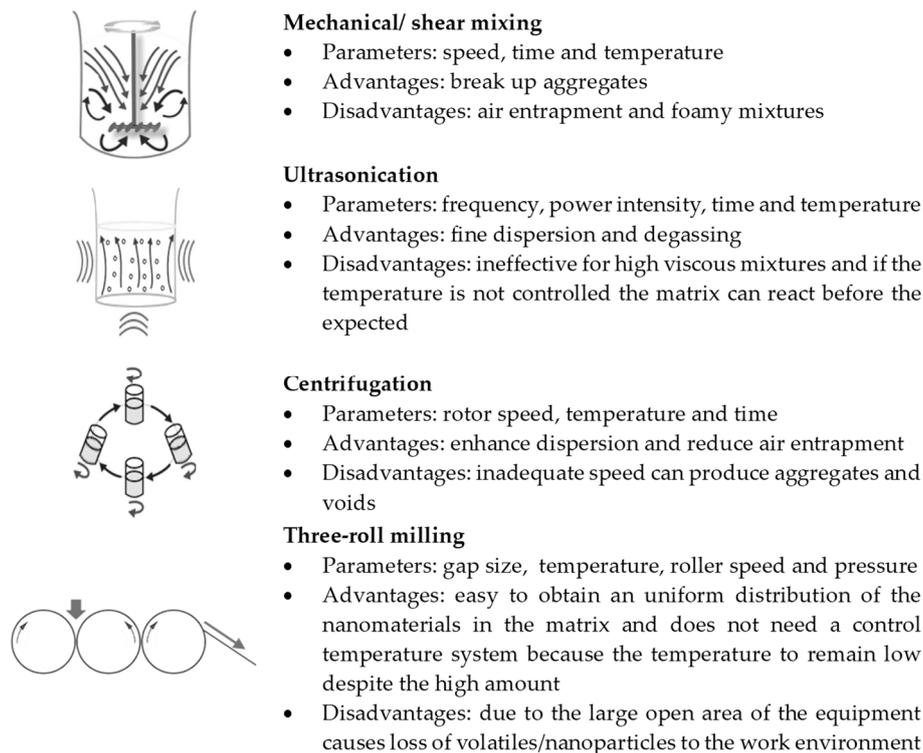
The combination between the remarkable structural performance of continuous carbon fibres (CFs) with the multifunctional properties of carbon-based nanomaterials allows the development of novel nanoengineered (multiscale) CFRP composites (Figure 2) with interesting synergies [1].



**Figure 2.** Typical scenario of the production of a multifunctional CFRP by incorporating nanofillers [1].

The combination of carbon-based nanoreinforcements with conventional fibre reinforcements in polymer composites may be achieved through different routes, namely, dispersing in the polymer matrix, growing on fibres, interleaving buckypapers and stitching the nanomaterials onto the fibres [24].

There have been various approaches to improve the dispersion and the interaction between the carbon-based reinforcements and the thermoset polymers, which can be divided into two main categories of chemical and mechanical approach. The chemical approach focuses on the creation of chemical bonding between the nanotubes and the polymer matrix. The chemical approach includes: (1) the creation of non-covalent bonding by the solvent and surfactant-assisted dispersion, and (2) the creation of covalent bonding by the surface functionalization of the nanomaterials. While the mechanical approach mainly employs the sophisticated mixing methods (Figure 3), such as: (1) dispersing the particles into the matrix with the help of sonication and or (2) by high shear mixing (three-roll milling) [25–30].



**Figure 3.** Main physical methods to disperse nanomaterials, created from [28–30].

In order for the nano modified thermosetting polymers to penetrate into the primary fibre tows, filtration effects need to be minimized, usually by using low loading fractions and small/short nanomaterials to produce the hybrids composites. Manufacturing processes for advanced composites include methods such as hand lay-up, resin transfer moulding (RTM), compression moulding, filament winding, autoclave curing, vacuum-assisted resin transfer moulding (VARTM), among others. Some of these advanced fabrication techniques enable structural composites to be manufactured with better compaction and low void fractions and, in turn, superior mechanical and other properties. Nevertheless, manufacture of high performance composites using nano modified prepregs with autoclave curing has been “the gold standard” established by aerospace industry [31,32]

Melt-mixing routes are commonly used to prepare CNT-polymer and graphene-polymer nanocomposites within the thermoplastics industry, making them available at large scale. Typically, the polymer nanocomposites are produced by twin-screw extrusion and are available in the form of pellets, ready for the application in industrial processes, as injection moulding, extrusion blow molding, filament drawing, among others [33].

### 2.3. Products

The typical properties of conventional CFRPs, including high stiffness, strength-to-weight ratio, fatigue tolerance and electrical conductivity are strongly dependent on the CFs orientation. After the great success of manufacturing high performance CFRP, scientists have continued exploring the world of carbon-based materials, since the out-of-plane properties of composites are mainly dominated by the insulating and brittle nature of the thermoset or more ductile thermoplastic polymers [1]. Hence, the modification of these polymeric matrices with carbon allotropes has proved to overcome some of those limitations [34]. Through the incorporation of nanomaterials, at ultralow percolation thresholds, advanced, lightweight and smart CFRPs with integrated novel functionalities have been successfully developed [35]. These nanostructures have brought various extraordinary properties such as electrical, mechanical, thermal and “smart” properties [36–39]. For example, the formation of a conductive network established between the well dispersed carbon-based nanomaterials within



- Trigeminal—the route uses the trigeminal nerve as an important way to transport from nose to brain, i.e., intracellular or axonal transport.

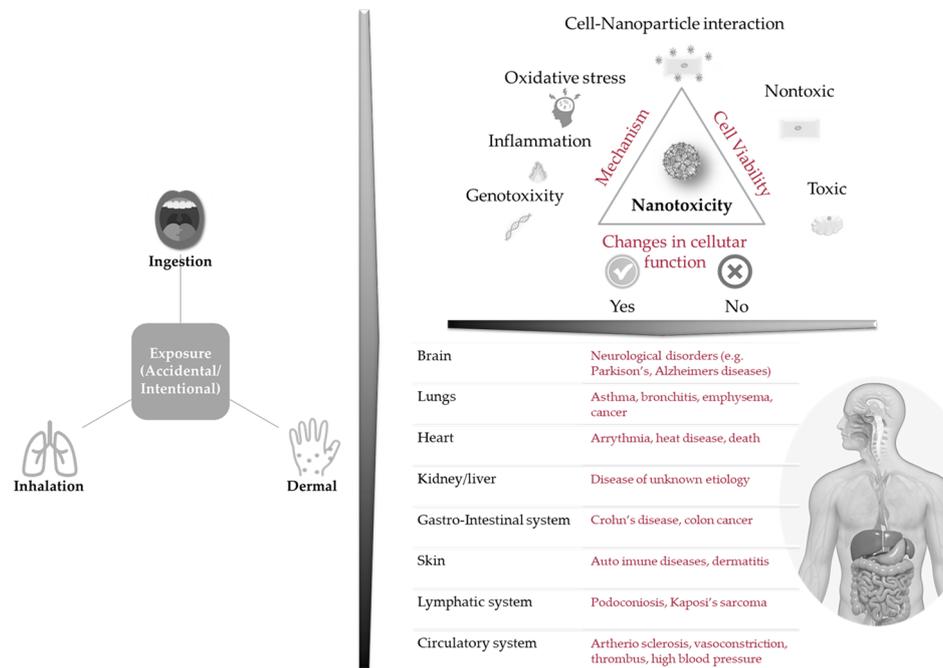


Figure 5. Potential interactions of carbon nano allotropes and possible consequences, created from [49].

The CNTs induce toxicity, such as oxidative damage in biological systems and influence the central nervous system, trough endothelial cell damage [46]. Additionally, due to the batch-to-batch variations nanoengineered materials parameters may change with time, implying possible changes in the toxicological effects (Figure 6). This means that CNTs and graphene need to be fully characterized, in short and long term, and have a specific toxicity (eco) assessment, as well as rendering hazard and risk evaluation [41,47,51].

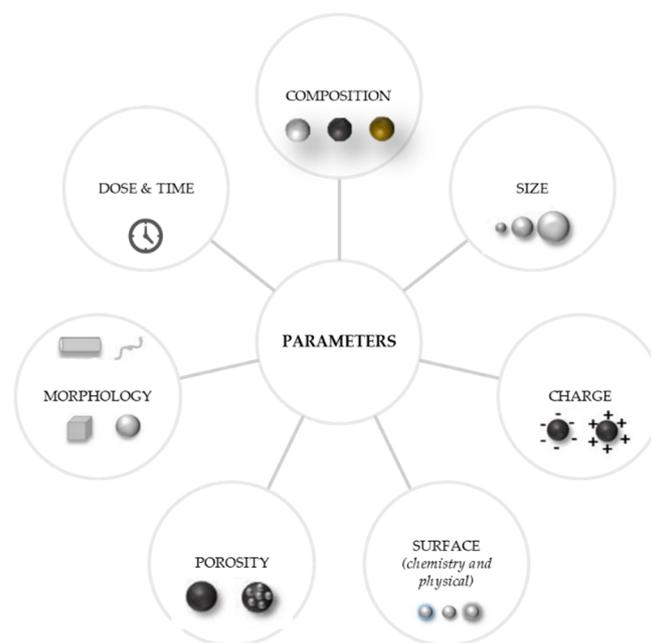


Figure 6. Key properties involved in nanotoxicity, created from [41].

Vascular effects induced by CNTs have been reported through different mechanisms. It may cause progression of atherosclerotic plaque, changes in blood pressure and heart rates, as well as vasomotor dysfunctions [52]. However, these drawbacks are more common with pristine CNTs, since functionalization may lead to less damage effects.

### 2.5. Safety

The production of CNT, graphene and other derivatives, their chemical functionalization, as well as the modification of polymers and CFRPs, by incorporating these nanomaterials, leads to different levels of the workers' exposure. From the synthesis to the different applications with the downstream nanoparticle use for further dispersion and processing into products, or surface treatment, different forms of exposure (e.g., powder, liquid and "solid" states) are involved [1].

Preventive safety measures must be applied to all workers (i.e., researchers, engineers, technicians, chemists and even managers) that are involved in the different phases of the production of CFRPs with carbon nano allotropes, although considering different levels of exposure [23]. A clear definition for limit levels of exposure is necessary for each role in the process, for each nanomaterial and for each process route. Moreover, the increasing evidence that people already with respiratory diseases are likely to be more susceptible to damage effects [53,54], for safety reasons the exposure limits and the likelihood of a person to work with nanoengineered materials need to be objectively evaluated. Safety data sheets must be provided for the life cycle of all nanoengineered materials [55]. They must include product, hazards, company identification, and safety exposure limits. The determination of Occupational Exposure Limits (OEL) [11] and users' limits are of paramount importance. Although admitting incertitude, some recommended exposure levels were presented, namely  $1 \mu\text{g}/\text{m}^3$  elemental carbon in a respiratory mass 8-h time-weighted average (TWA) concentration [56], but the knowledge in this area still does not ensure nanotechnology safety [57].

Accounting for the considerations above, it can be stated that for safety purposes, scientific and technical studies must be done to answer the following questions [58]:

- How to overcome limitations of current technologies and techniques?
- What are the most important physical and chemical properties with respect to biological behavior of ENM, in short, medium and long time?
- What should be the degree of accuracy and how to measure accurately?
- What are the ignition and explosive properties, and their potential risks?

It has been stated [58] that Personal Protection Equipment (PPE), if used properly, may be an effective way to reduce damage risks when dealing with ENM.

### 2.6. Risk Management

Naturally, a well-defined risk management evaluation requires the identification and characterization of the hazards type expected to occur, exposure assessment and potential risks. Although there are some common features for ENM, in general, a methodology for a given group of ENM may not be adequate for another one. Hence, it is important to clearly characterize the nanomaterial and its potential hazards. Volume Specific Surface Area (VSSA) together with the nanoparticle size have been reported as complementary criterion for their definition [59].

Exposure to nanomaterials, particularly to ENM, can occur under research activities during production (with release of nanoparticles to air and water), handling, during service applications subjected to diverse ageing effects and product end of life, with possible re-use, recycling, waste treatment and final disposal. For those reasons, the integration of Life Cycle Analysis (LCA) into risk assessment is highly recommended. In this context, the milestones indicated in Table 2 are expected to be reached by 2025 [12].

**Table 2.** Risk prediction and management tools for 2025, adapted from [12].

Milestone	Topic	2025
Risk assessment (RA)	Proactive risk management	With the use of risk banding tools and effective control measures development practice in 201, high throughput screening approaches will be validated by 2020
	Tools	RA-enabled LCA/Integration into decision tools
Epidemiology and health surveillance	Health effect Register Study design	Implementation of the markers Implementation of results for regulations Longitudinal studies started
Databases	Infrastructure Ontologies	IT procedures for automatic uploading Automatization of ontologies
Risk management	Risk perception and guidance	Guidance on risk evaluation
	Prevention through design approach	Integration of safe-by-design approaches into development stages of new NMs and their applications

Aiming to ensure the health and safety of workers, employers have the obligation to conduct regular risk assessments—as specified in the “Framework” Directive 89/391/EEC—in every aspect related to their work, particularly when dealing with ENM. Moreover, the Directive 98/24/EC on chemical agents at work imposes stricter rules for work risk management regarding these substances—particularly, the hierarchy of prevention measures that strengthens elimination or substitution as priority measures. This can also be applied to nanomaterials, as they fall within the definition of “substances” [60].

There is no specific legislation applicable to nanoparticles (NP) and nanomaterials. Some International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM International) and British Standards Institution (BSI Group) standards applied to these materials are beginning to emerge. In the traditional risk assessment, the exposure doses are compared to the occupational exposure limit values (OELs). Since there are no specific OELs for NP, these standards propose, as a pragmatic orientation, the limit values shown in Table 3 [60].

**Table 3.** OELs for nanomaterials (NM) [60].

Description	Benchmark Exposure Levels
Fibrous; a high aspect ratio insoluble NM	0.01 fibres/ml
Any NM which is already classified in its molecular or in its larger particle form as carcinogenic, mutagenic, reproductive toxin or as sensitizing (CMRS)	0.1 × OEL
Insoluble or poorly soluble NM not in the fibrous or CMRS category	0.066 × OEL
Soluble NM not in the fibrous or CMRS category	0.5 × OEL

In addition, the World Health Organization has issued guidelines for the protection of workers to minimize risks when dealing with nanomaterials [61].

### 2.6.1. Risk Assessment Methods

Risk assessment involves solving equation 1 and can be evaluated by using semi-quantitative analyses. Recommended values have been issued by several institutions, such as the French Agency for Food, Environmental and Occupational Health & Safety method (ANSES), from France; Control Banding Nanotool (CB Nanotool), from the United States of America—National Institute for Occupational Health and Safety (NIOSH); École Polytechnique Fédérale de Lausanne method (EPFL),

from Switzerland; Guidance working safely with nanomaterials and nanoproducts (GWSNN), from The Netherlands; Istituto Superiore per la Prevenzione e la Sicurezza del Lavoro (ISPESL), from Italy; Precautionary Matrix for Synthetic Nanomaterials (PMSN), from Switzerland; and Stoffenmanager Nano, from The Netherlands [62].

$$Risk = Hazard \times Exposure \tag{1}$$

Table 4 shows an overview of hazard factors defined by each method for a given situation [62].

**Table 4.** Hazard band factors [62].

Hazard Factor	ANSES	CB Nanotool	EPFL	GWSNN	ISPESL	PMSN	Stoffenmanager
Toxicity (nano and/or bulk material)	•	•		•	•		•
Solubility	•	•		•		•	•
Fibre form (particle shape)		•	•	•			•
Reactivity	•	•				•	
Size		•			•		•
Fire and explosion					•		

Other nanomaterial grouping approaches can be obtained in BSI [63], NIOSH [64] and BAuA—The Federal Institute for Occupational Safety and Health [65].

In Table 5 the factors that could determine the worker’s exposure are presented.

**Table 5.** Exposure (or likelihood) band [62].

Exposure Factor	ANSES	CB Nanotool	EPFL	GWSNN	ISPESL	PMSN	Stoffenmanager
Quantity		•	•			•	•
Duration/ frequency (time) factor		•			•	•	•
State of material (e.g., solid, liquid)	•		•				•
Release of nano-objects (e.g., dustiness)	•	•		•		•	•
Aggregation/ agglomeration			•		•		

REACH [66] and ECHA [67] may be considered as the most updated documents regarding regulations and guidance for nanomaterials grouping [51]. Risk estimation and characterization is defined by REACH [66] and comparing exposure and hazard levels provides the estimate of a Risk Characterization Ratio, defining process categories versus environmental risk categories. It also presents an overview of selected risk assessment tools [68].

### 2.6.2. Research

Nanotechnologies present new challenges regarding risk evaluation and management. Hence, besides technological developments, research has to be performed for risk evaluation based upon quantitative data on toxicology and ecotoxicology, and, when necessary, adjusting the assessment

methodology [69]. Answering to future disruptive scientific and technical challenges in nanoscience's and nanotechnologies, while keeping in mind health and safety concerns, is essential to ensure the competitiveness and economic growth.

### 2.6.3. Industry

Dealing with polymeric nanocomposites processing requires a safety analysis and preventing risks, which is the base of the Framework Directive 89/391/EEC. Health and safety at the workplace is the main driver of this Directive, implying that risk assessments regularly made by the employer. However, there is nothing specific for nanomaterials. Thus, the suitability of the legal framework is uncertain or even speculative. Being chemistry involved, nanomaterials are likely to be considered under the chemicals regulations [60].

A proper legal framework is barely needed in order to regulate the use of NM, and ensure confidence from cradle to grave [70]. Beyond consistency and avoiding market distortions, harmonized regulations will guarantee risk minimization and ensure workers' health and environmental safety.

### 2.6.4. Application

Even embedded in a matrix, nanoparticles release can occur during all stages, i.e., from cradle to grave. The probability of exposure must be analysed for the entire life cycle of the nanomaterial, being the risks evaluation made applying a model close to the one use for natural disasters [60]. Up to now, there are few and limited detailed risk or life cycle studies on the specific impacts of nanomaterials. Moreover, the waste must be removed from the system following specific protocols; once the cleaning operation is finished, all waste has to be stored in appropriate containers for further disposal control [69,71,72].

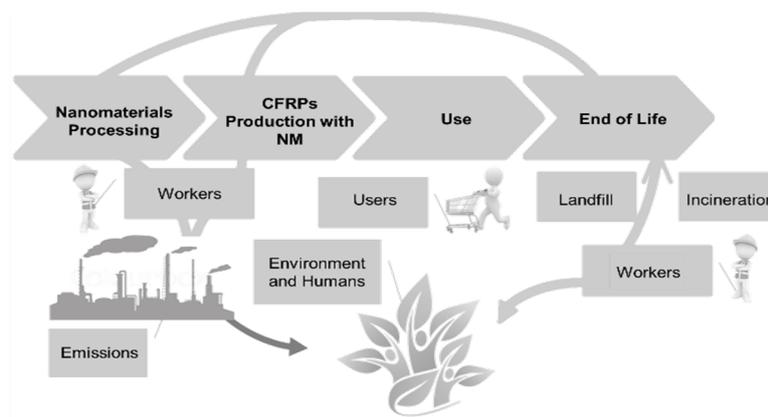
Prevention is the main action to mitigate possible risks related to nanoparticles and this can start in the design phase, followed by the safety in the manufacturing process and safe procedures for the use of the products.

Risk assessment and management must be considered in a life cycle approach and include the effect of specific nanomaterials in several environmental situations such as air (can nanoparticles with <70 nm pass through HEPA filters), landfill, waste incineration, sewage and sewage treatment plants and water [58,73,74].

## 3. Discussion

CNTs and graphene are valuable raw materials with numerous application in several sectors, yet legitimate concerns about their potential adverse effects on human and environmental health and safety need to be addressed. CNTs, due to their morphology (fibre type) have higher potential to be harmful than other carbon particles forms (i.e., spherical and plates). They can have a higher contact area with the cell membrane in comparison with particles of different shapes. CNTs are considered hazardous when thinner than 3  $\mu\text{m}$  and longer than  $\sim 20 \mu\text{m}$ , or when no biodegradation in the lungs by dissolving or breaking is possible. Moreover, below these dimensions, there is also a clear evidence for pulmonary and intraperitoneal carcinogenicity of bio persistent nanofibres, and certain MWCNTs [1,75]. Pulmonary fibrosis has also been highlighted as an effect of MWCNT exposure [76,77]. For graphene, however, there are only few studies that have assessed its toxicity, evidencing that some forms of this nanomaterial can be a health hazard [47,78,79].

The workers' exposure to health risks might occur during production, downstream use for further processing or dispersion into products, and application or treatment of CNT/graphene modified CFRPs. During the CFRPs production carbon-based nanomaterials can pass through different "states" (powder, in a liquid resin and inserted into the solidified polymeric matrix), leading to different exposure degrees, as can be seen in Figure 7 [1].



**Figure 7.** Possible exposures during life-cycle of CFRP's modified with carbon allotropes [1].

Polymeric materials, including NC, are considered chemicals. Hence, some of the legislation related to chemical agents and REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) applied [60].

The Organization for Economic Co-operation and Development (OECD) has recommended the application of existing international and national chemical regulatory frameworks to deal with the risks associated with manufactured nanomaterials (NM). Protocols that have been applied to chemicals (based on legal frameworks for these products) can be applicable to NM [80].

The actual regulation is normally supported on parameters likely to be unsuitable for some nanotechnology applications. For example, thresholds are often defined in terms of production volumes or mass, below which a substance may be exempt from regulation. These thresholds should be reviewed and, when appropriate, modified. But, while specific NP regulations are not established, proactive approaches must be followed [60].

It has been reported [46] that the use of CNTs in neurology can only be made in a safer way, if they have a high degree of purification, are well tailored and properly coated.

Costs are always an issue related to health and safety. Although health and safety are normally regarded as cost raisers, the evaluation must be done with a holistic approach. In fact, the reduction of production costs must not be used at expenses of safety. Nanosafety must be included in the development phase, giving guidance to the technology selection and subsequent improvement of safety and sustainability [33]. To have a global picture of the calculation of final cost for safety, a list of the main parameters has [46,73] been designed and must be implemented. Although not exhaustive, the following list can be considered, by order of importance:

1. Employees,
2. Identification and compliance with regulations,
3. Risk and vulnerability analysis,
4. Emergency response plans, related drills and training,
5. Personnel training, refreshments, role compliance monitoring,
6. Maintenance, inspection and monitoring of equipment and instrumentation,
7. Fire and explosion protection,
8. Personal protection equipment,
9. Investigation of incidents and near misses,
10. Hazardous material transportation,
11. Alarms and control equipment,
12. Passive barriers,
13. Construction of code-certified buildings,
14. Costs related to raw materials,

15. Costs of equipment,
16. Insurance cost,
17. Security cost,
18. Decommissioning costs,
19. Software related costs.

An effective health and safety program will reduce potential incidents and, consequently, worker's compensation insurance costs [74].

Healthy and safety from cradle to grave will ensure safe innovations in nanomaterials and products. Nanosafety strategies must start by information gathering to achieve risk mitigation, followed by hazard and exposure assessment, risk characterization and monitoring [68]. There is no consensus regarding safe occupational exposure limits for specific CNTs. However, 50 mg/m<sup>3</sup> is indicated [3] as limit concentration based on risk estimation of noncancerous adverse lung effects. A recommended exposure limit—REL for a working life of 45 years is referred to be 1 µg/m<sup>3</sup> [56,81]. Moreover, the proposed occupational exposure limit—OEL for CNTs is suggested to be in the range of 1 to 50 µg/m<sup>3</sup> as an 8 hours' time weighted average—TWA µg/m<sup>3</sup> [56]. NIOSH also recommends a REL 1 µg/m<sup>3</sup> for 8-h TWA of exposure to CNTs and CNFs of respirable carbon element [56,81].

From the general review, several authors suggested that the application of the precautionary principle can be used as a guideline in the environmental decision making process [81].

It is accepted, in general, that CNTs have higher potential to be harmful than other carbon particles shapes (i.e., spherical and plates), due to higher contact area with the cell membrane in comparison with other particle shapes. They are considered hazardous when below 3 µm diameter and longer than ~20 µm, or when no biodegradation in the lungs by dissolving or breaking is possible. Besides that, below these dimensions, there is also clear evidence for pulmonary and intraperitoneal carcinogenicity of bio persistent nanofibers, and certain MWCNTs. Furthermore, pulmonary fibrosis has been highlighted as an effect of MWCNT exposure [33,76,82].

The production of goods incorporating carbon nanomaterials involve the workers' exposure during the nanomaterials production, downstream use for further processing or dispersion into matrix materials, and application or treatment to form the final products. Along the different stages of carbon-based nanomaterials processing and handling, different exposure degrees are attained.

It should be noted that besides human impacts, the carbon-based nanomaterials also exhibit toxicity to plants, other animals and microbes [83–85].

Eliminating the risk at source by replacing the potentially hazardous substances by safer ones appears to be an attractive and cost-effective solution; however, it is hard to apply since the CNTs and graphene-based products have unique properties desired by the industry.

#### 4. Proposals

Exact exposure assessment methods for nanoparticles have not yet been established, and the occupational exposure limits for carbon-based nanomaterials have not been set, leading to inconclusive results and sometimes to inadequate protection measures [33,76,82].

A guidance on the protection of the health and safety of workers from the potential risks related to nanomaterials at work from the European Commission is available for safe practices [86]. Different universities, as well as research labs, have also provided guides on their websites for working with nanomaterials, which mainly involve following standard protocols similar to those existent for other materials with known or uncertain toxicity, whose goal is mainly to prevent any type of exposure [87,88].

In this section, a proactive view is proposed aiming to contribute with general guidelines on technical, maintenance, evaluation, personal protection (PPE) equipment and personnel training to deal with CNT and nano graphene products in research, manufacturing and use with composite materials.

#### 4.1. Technical

Technical measures comprise the infrastructures, construction of buildings, warning systems, installations and building layout. These measures are designed and implemented in the building, to ensure the collective protection of the workers, against multiple risks that may affect their health or safety at work.

The effect of the controls can be expressed as the protection factor (PF). It is defined as the ratio of exposure level (either mass-based or particle-based) without the controls divided by the exposure level with the controls (PF > 1 controls reduce exposure; a PF of 10 indicates that controls reduce exposure by 90%) [61].

##### 4.1.1. Laboratory

By using appropriate equipment and proper lab practices, it is possible to reduce the risks associated with the manipulation of nanomaterials [43,89].

The recommended technical protective measures in the laboratories are the following [90]:

- Ventilation:
  - With renewal without recycling 5–10×/h,
  - With at least a sealed F7/H14 filter (EN 779) for exiting air, since these filters have 80–90% average efficiency for 0.4 µm particles,
  - Low pressure room,
  - Capture of the contaminate air at the source.
- A seamless and impermeable resin floor with coving between the floor and wall will minimize the risk of accumulation in cracks and gaps of nanomaterials, by making at the same time easier to clean and easily remove contaminants from the area.
- Manipulation under fume hood (compulsory).
- SAS entrance and exit (simple).
- Safety shower.

##### 4.1.2. Industry

The recommended technical protective measures should be almost the same that are used in the laboratory, although it must be ensured that the low-pressure room is >20 mPa and that the SAS entrance and exit is double [90].

For SMEs (Small and Medium Size Enterprises), costs of some controls may become highly expensive, if not prohibitive. Hence, these companies should consider alternatives out of their organization as a strategy to follow controls within a restricted budget, such as [74]:

- Cooperation with academia and/or larger companies to have access to a high level of controls.
- Consider the acquisition of used laboratory equipment, but bear in mind to ensure they operate under the correct specifications prior to use.
- Work with local economic and development groups to promote the importance of engineering controls as enabler tools for nanotechnology commercialization for SMEs and promoting the benefits of protecting workers, environment and community at large.
- Include discussion of EHS – Environmental Health and Safety rules in the business plan and budget for high-level of controls possible needed.

Moreover, SMEs should consider the possibility to share, among themselves, high-level of controls equipment.

## 4.2. Personal Protection Equipment

Personal protection equipment (PPE) are devices or appliances designed to be used by an individual worker for his protection against one or more health and safety hazards. When working with nanomaterials the personal protective equipment should be preferably disposable, however, when it is not possible it must be cleaned regularly or after use [84].

The principle of hierarchy of controls suggests that the first control measure should be to eliminate the source of exposure. This will reduce implementing control measures that are more dependent on workers' attitudes. Involvement with PPE should be used only as a last resource. In the absence of appropriate engineering controls PPE should be used, especially respiratory protection, as part of a respiratory protection programme, including fit-testing [61].

### 4.2.1. Laboratory

Laboratories typically involve shorter work periods and exposure to smaller quantities of nanomaterials. Hence, the PPE that should be adopted is [84,85,90,91]:

- Masks with P3 filters are advised for respiratory protection.
- To protect the eyes/face, use a face shield or lab goggles.
- Protection of the body parts with overalls with hood (Tyvek<sup>®</sup> style), since nonwoven clothing is more efficient against penetration of NP than woven cotton.
- The use of two or more pairs of disposable gloves (nitrile, vinyl, latex, Neoprene<sup>®</sup>) should be adopted and frequently replaced, especially for exposure to nanomaterials in liquid phase.

There are indispensable considerations and recommendations for the handling and disposal of nanomaterials, including graphene and related derivatives.

Regarding their handling, research and working personnel should always wear appropriate clothing and PPE, which include lab coats, gloves, well-fitted masks and appropriate eye protection [8,89,92]. These materials should be in sealed containers, stored in closed cabinets and samples' size should be limited to small amounts and manipulated carefully, in order to avoid spills and lower the risk of dermal exposure and the risk of airborne contamination [8,89]. Special considerations during weighting or synthesis processes should also be undertaken. Free particles should not be manipulated on the lab bench. Opening up sample recipients and weighing processes should be carried out under a fume hood or at least in a glove box dedicated to that process [8,89,93]. Although the risk of exposure is higher when handling powders than when working with dispersions [10], these should also be contained, particularly if subjected to ultrasonication. Furthermore, these particles should not be disposed of as general waste but should be bagged, labelled as nanoscale, and sent out for authorized authorities as hazardous waste. If dispersed, the medium should first be neutralized if it is the case and should be disposed of according to the hazardous chemical waste guidelines [8,89,93]. Adequate cleaning procedures are also necessary. Work areas should be cleaned after use or at a minimum at the end of each day. Any small powder spills should be removed by using wet wiping methods. The contaminated surface should be cleaned until no trace of nanomaterial is visible. Larger spills should be cleaned with a vacuum cleaner equipped with a HEPA filter. Research laboratories should be routinely cleaned and checked regularly to ensure the maintenance of cleanliness. In addition, all devices and equipment meant to prevent or eliminate work hazardous materials should undergo maintenance and be checked regularly [8,92,93]. The regular realization of particle surveys is also important to quantify any airborne particle contamination, since these can help with risk reduction measurements if any contamination is detected, such as the rebalancing of the laboratory ventilation systems [8].

### 4.2.2. Industry

The personal protective equipment that should be used in industry is similar to the laboratory. However, in the industry, the work periods with nanomaterials are longer and they use higher quantities

of nanomaterials in their products, the exposure is higher. Therefore, it is necessary to take into account that the following should be additionally used [90,91,94,95]:

- A powered air respirator, because ensures better comfort for longer work periods (it is recommended this system if the work lasts over 2 h). However, for shorter periods of exposure a P3 filtering mask can be used.
- Similar to the laboratories, it should be used two or more pairs of disposable gloves (nitrile, vinyl, latex, Neoprene®), but they should be replaced with higher frequency.

#### 4.3. Training

Education and training are important tools for informing workers about hazards and protection measures to ensure their safety and their performance.

In training, an aspect not always considered, is Prevention through Design (PtD), i.e., the concept of Design with the objective to rule out occupational hazards to protect workers [74]. Hence, it is recommended to include the former concept in educational and training packages.

##### 4.3.1. Laboratory

Before having to work with nanomaterials, all laboratory workers should undergo pertinent training, in which they learn about health issues related to the use of these particles, standard procedures for manipulating these materials and precautions to prevent exposure, hygiene requirements, and what should be done in case of incident handlings [92]. All of these safe work instructions should also be documented in a regularly updated and revised document, written in a clear and concise manner, in order to allow all users (especially new ones) to be aware of all the risks associated with these materials and all the procedures for safe handling and laboratory cleaning [8].

The training should be firstly basic training for the laboratory practice. Then, it must be complemented with continuous training about nano manipulation, since regular discoveries are made regarding the use and safety issues of these materials. Besides, the training should be complemented with written working procedures [90].

##### 4.3.2. Industry

It is suggested [61] as a best practice that workers potentially exposed to manufactured nanomaterials (MNM)s should be educated on their risks and trained in how they can best manage the risks and protect themselves. Besides following current guidelines, education and training should focus on those aspects of manufactured nanomaterials that are additional to, or different from, education and training in the safe handling of bulk material chemicals. Hence, the following topics should be included [61]:

- Hazards are specific to MNMs and different from the bulk material.
- Hazard classes are assigned to MNMs.
- Routes of exposure are important which workplace exposures have been measured and which tasks put workers most at risk.
- How proposed OELs can be interpreted.
- When and how control banding, specific controls and PPE for MNMs can be used.

Normally, the workers face unknown risks regarding the exposure to nanomaterials, since the legislation considered that the risks of nanomaterials are the same as the micro materials. So, a deeper worker education and training initiatives are needed to prepare the nanotechnology workforce as the field continues to develop. Similar training that is used for laboratories should be performed, although with more frequency and the written working procedures should be regularly updated [90,96].

#### 4.4. Maintenance

Regular maintenance is essential to ensure safety and reliability of the workplace, since the lack of maintenance can lead to dangerous situations, accidents and health problems.

##### 4.4.1. Laboratory

In the laboratories maintenance activities, the workers should [90,97]:

- Perform the separation of the laboratory clothes from the outside ones (compulsory).
- Use safety containers for transportation of nanomaterials.
- Store in specific areas and separate cabins the nanomaterials. These cabinets must carry an appropriate danger label.
- The workers that handle the nanomaterials in the laboratory should be the ones that cleans the laboratory.
- The cleaning process should be wet to avoid the dispersion to the working atmosphere of the nanoparticles.
- The residues should be treated as chemical/hazardous waste and deposited in double bagging with a label that indicates the presence of nanomaterials in those wastes and include available information characterizing known and suspected properties.
- In the case that nanoparticles are accidentally split, the workplace must be cleaned immediately with a wet damp towel. Under no circumstances may residual materials be blown off the surface, particularly in the case of nanomaterials.
- Use the same protective equipment's during the cleaning and maintenance activities.
- Laboratory responsible must supervise the cleaning and maintenance activities.

##### 4.4.2. Industry

In the industry, the same maintenance procedures that are used in the laboratories should be adopted [90]. It should be considered that maintenance and cleaning operations may generate aerosols and workplace contamination increasing the risk of exposures for workers. During preventive maintenance, it is likely that safety devices (such as filtration elements) are "disconnected", which means the workers are immediately exposed if an error occurs. This implies a high risk of exposure that must be managed with well trained workers [33].

#### 4.5. Application of Safety Guidelines

To enforce the implementation of the safety guidelines, inspections should be conducted in parallel with other control actions.

##### 4.5.1. Laboratory

Besides regular inspections made by a health and safety specialist, to ensure the application of the safety guidelines in the laboratories the following measures should be also applied [86]:

- Restricted access to the room (magnetic card access control system)
- Evidence about exposed people + board to record presence
- Medical surveillance to all persons that works with nanomaterials (once a year).

##### 4.5.2. Industry

In industry, procedures similar to laboratories should be adopted, although besides the regular inspections, annual audits should be also performed and the medical surveillance should be carried out twice per year to all workers that handle nanomaterials [86].

Table 6 presents the proposed Occupational Exposure Limit Values for MNMs.

**Table 6.** Proposed Occupational Exposure Limit Values for MNMs Adapted from [61].

Category	NM and Specifications	OEL Name	Mass Concentration ( $\mu\text{g}/\text{m}^3$ )	Particle Concentration (particle/mL, fibres/ $\text{cm}^3$ )	Surface Concentration ( $\text{nm}^2/\text{cm}^3$ )
Inhalation exposure: general MNM approach					
MNM	Fine particle matter $\leq 2500$ nm	BOEL	30	ND	ND
MNM	Airborne particles from nanotechnology process	PCVs	ND	3 times L3PC for more than 30 min	ND
Inhalation exposure: categorical approach					
Fibres	Non-entangled fibrous NM	Acceptance level (default), respirable fraction	ND	0.01	ND
Fibres	Fibrous NM	BEL	ND	0.01	ND
Fibres	Carbon nanofibers CNFs	OEL	ND	0.01	ND
Fibres	Carbon nanotubes CNTs, insoluble NM with high aspect ratio $< 3:1$	NRV	ND	0.01	ND
Inhalation exposure: specific MNM approach					
Carbon	Multi-walled carbon nanotubes MWCNT 10nm	INEL	1	ND	ND
Carbon	MWCNT 140 nm	INEL	2	ND	ND
Carbon	Carbon nanotubes CNTs	No effect concentration in air	2.5	ND	ND
Carbon	Carbon nanotube group, SWCNT, DWCNT, MWCNT	OEL 15 years	30	ND	ND
Carbon	All CNTs and nanofibres	REL respirable elemental carbon	$< 1$	ND	ND
Carbon	MWCNT bay tubes	OEL Inhalable fraction	50	ND	ND
Carbon	MWCNT	DNEL chronic inhalation, systemic immune effect	0.67	ND	ND
Carbon	Fullerenes $\text{C}_{60}$	INEL	7.4	ND	ND
Carbon	Fullerenes $\text{C}_{60}$	OEL (PL) 15 years	390	ND	ND
Dermal exposure					
Carbon	MWCNT	DNEL dermal chronic exposure, assessment factor 3	5.9 $\mu\text{g}/\text{kg}$ body weight	ND	ND
Carbon	MWCNT	DNEL dermal chronic exposure	17.7 $\mu\text{g}/\text{kg}$ body weight	ND	ND
Acute short-term exposure					
MNM	Airborne particles from nanotechnology processes	PCVs single short-term measurement	5 times the local particle reference value	ND	ND
Carbon	MWCNT	DNEL acute inhalation, systemic immune effect	4.02	ND	ND
Carbon	Fullerenes $\text{C}_{60}$	INEL short-term, inhalable fraction	44.4	ND	ND
Carbon	MWCNT	DNEL acute inhalation, pulmonary effect	201	ND	ND
Carbon	MWCNT	DNEL dermal acute exposure	106 $\mu\text{g}/\text{kg}$ body weight	ND	ND
Carbon	MWCNT	DNEL dermal acute exposure, assessment factor 3	35.5 $\mu\text{g}/\text{kg}$ body weight	ND	ND

BEL: benchmark exposure level; BOEL: benchmark occupational exposure level; BSI: British Standards Institute; CNF: carbon nanofiber; CNT: carbon nanotube; DNEL: derived no-effect level; DWCNT: double-walled carbon nanotube; INEL: indicative no-effect level; MNM: manufactured nanomaterial; MWCNT: multi-walled carbon nanotube; ND: no data; NM: nanomaterial; NRV: nano reference value; OEL (PL): occupational exposure limit period-limited; OEL: occupational exposure limit; PCVs: particle control values; REL: recommended exposure limit; SWCNT: single-walled carbon nanotube.

Other exposure limits can be identified. For instance, a REL of  $1 \mu\text{g}/\text{m}^3$  EC for CNTs and carbon nanofibers is proposed as an 8 h TWA respirable mass concentration [5,56]. BSI [63] suggested a BEL of  $0.01 \text{ fibres}/\text{cm}^3$  and this has been established in UK, Germany and Switzerland [5,98].

#### 4.6. Product Life Cycle

Research, development, and manufacturing of products with nanomaterials must take the responsibility of environmental, safety and health impact of products at specific points during the life cycle of the material from design up to disposal. In other words, they must assume product stewardship. Safety data sheets must be provided and health and communication standards followed. Besides product and hazards identification, composition, first-aid fire-fighting and accidental release measures, handling and storage, properties (physical and chemical), stability and reactivity, Product Stewardship may also include ecological, toxicological, disposal and transport information [80,99,100]. Moreover, it is equally important to include product safety testing, correct labelling, dangerous issues during transportation, as well as a customer service.

### 5. Conclusions

Up to now, there is not enough knowledge on the possible adverse effects of CNTs and nano graphene to ensure a complete workplace safety. Considering that CNTs and nano graphene are increasingly used, and it is unlikely that in the near future, scientific and industrial entities stop using nano-modified products, it is imperative to establish guidelines to handle these materials.

The identification of the potential hazards of CNTs and graphene to human health, during the development of products with these materials, is imperative. Moreover, manufacturing “safe” end products containing these nanomaterials will enhance the confidence of end-users, workers, researchers and other relevant stakeholders.

In the present research work, some practical and simple safety and health management actions, (such as technical, PPE, training, maintenance, application of safety guidelines and product life cycle measures) for laboratories and industries that use nanomaterials in their workplaces, based on the current state of knowledge, are proposed. These should be easily updated when more scientific data will become available. Monitoring, adaptation, control, and review of measures in place have a high importance.

Owing to an insufficient knowledge and application of the precautionary approach in practically all methodologies for management of CNTs and nano graphene safety currently available, proactive measures have an ‘over-protection’, that probably will be softened as knowledge will increase, are generally better than having an insufficient protection; this environment has an important role in educating people.

Thus, more research and collaborative efforts on nano safety are required in order to prevent, minimize the potential hazards of nanomaterials and to fill the existing gaps.

Finally, to overcome health and safety concerns related with CNT and graphene products it should be use Prevention, Precaution and Proactivity (in case of uncertainty go beyond what is commonly required) measures. Above all, Design Integrating Safety, Sustainability and Salubrity (DI3S) should be applied as soon as possible in the product development industries; to safeguard that the manufacture CNTs and graphene products do not have negative impacts in the health and safety of the workers, consumers and environment, making possible for the companies to achieve a truly safe and sustainable management.

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