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Review

Engineered Nanomaterials for Aviation Industry in COVID-19 Context: A Time-Sensitive Review

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Abstract: Engineered nanomaterials (ENMs) are catalyzing the Industry 4.0 euphoria in a significant way. One prime beneficiary of ENMs is the transportation industry (automotive, aerospace, rail car), where nanostructured multi-materials have ushered the path toward high-strength, ultra-impact-resistant, lightweight, and functionally graded engineered surfaces/components creation. The present paper aims to extrapolate much-needed ENMs knowledge from literature and its usage in the aviation industry, highlighting ENMs contribution to aviation state-of-the-art. Topics such as ENMs classification, manufacturing/synthesis methods, properties, and characteristics derived from their utilization and uniqueness are addressed. The discussion will lead to novel materials' evolving need to protect aerospace surfaces from unfolding SARS-COVID-19 and other airborne pathogens of a lifetime challenge.

Keywords: engineered nanomaterials; aviation industry; surface coatings; COVID-19

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1. Introduction

Innovative built materials have empowered the strength and durability of vehicles. For more than two decades, their integration has benefited the aviation industry in numerous ways: structural lightweight, aerial surveillance by sensorial technologies, high-impact erosion protection from dynamic fatigue, structural insulation from lightning strikes, etc. With the COVID-19 pandemic surge, this industry needs to mount its effort and work with innovative surface protective technologies to build surveillance around pathogens. Engineered nanomaterials (ENMs) and coatings have played an essential role in enhancing surface wear and friction properties of components in high-stake space and defense sectors. However, the priority now has shifted from being luxurious to a necessity.

The antiquity of nanomaterials has instigated somewhere near the big bang with the formation of nanoparticles in space after comets, asteroids, and meteorites have collided and formed nanoparticles of various compositions. Bestowing to the International Organization for Standardization (ISO), the preface "nano" symbolizes a size ranging between 1 to 100 nm [1]. Consequently, nanomaterials are more significant than a single atom with ultimate control over discrete material properties, some of which are relevant to the aviation industry:

Mechanical:

- Uttered by particle size, i.e., Griffith criteria, morphology, interfacial strength (e.g., chemistry and roughness).
- High surface area and aspect ratios, radically changing nanomaterial properties as opposed to bulk material properties.

- Possess perfection in molecularity, extremely ordered, and have defect-free structures.

Thermal:

- Particle size and interatomic voids can control the thermal conductivity.
- Particle size and surface properties can control and affect the emissivity.

Electrical:

- In terms of conductivity, bandgap energy, current density, and thermoelectric properties can be influenced by nanostructure and impurities.
- Threshold and field emission can be enhanced using high aspect ratios.
- Nanoscale dimensions can influence radiation resistance.

With the emerging need to utilize ENMs potential for biomedical and particularly health emergency concern, nanomaterials need to be researched for. In this particular context, a new dimensionality concerning ENMs future will be the core novelty in this discussion. The paper's structure is further divided into six sections: Section 2 deals with the classification of ENMs and their correlation with the aviation Industry. This has a natural evolution to the nanomaterials' proposed understanding in the different parts of aviation science. Section 3 presents an in-depth study on the properties of ENMs and their particular applications. Section 4 deals with ENMs in developing aerospace focused antiviral films/coatings, the current context of COVID-19. This section will also present a methodology for permanent disinfection of the surface from the coronavirus. Section 5 deals with the ENMs synthesis methods and their detailed classification, a comparison of commonly used techniques is also presented in this section. A summary and prospect of ENMs have been presented in Section 6.

2. Classification of ENMs and Their Correlation with Aviation Industry

Nanomaterials are classified on the number of dimensions: (i) zero-dimensional (0-D), (ii) one dimensional (1-D), (iii) two dimensional (2-D), and (iv) three dimensional (3-D), going from nanoparticles (e.g., quantum dots) to bundles of nanotubes as well as multi-nanolayers. Table 1 summarizes the most ENMs used in airframe structure, aero-engine parts/components, and aircraft electro-communication systems [1–4].

Table 1. Most ENMs used in components related to airframe structure, aero-engine parts, and aircraft electro-communication systems.

Component Parts	Nanomaterials Used	Mechanical Properties
Airframe structure	1. Carbon nanotube (CNT)-based polymer composites	Young's modulus, high specific strength, crash resistance, and thermal performance.
	2. Nanoclay reinforced polymer composites	Barrier properties, thermal and flame retardant properties.
	3. Metal nanoparticle incorporated composites	Extraordinary electrostatic discharge and electromagnetic interference (EMI) shielding properties which are resistant to lightning strikes.
Aero-engine parts/components (nanocoatings)	1. SiC nanoparticles in SiC-particle-reinforced alumina	Crack healing, improved high-temperature, high strength, and high creep resistance.
	2. TiN nanocrystallites embedded in amorphous Si_3N_4	Wear-resistant coatings.
	3. Nanocomposite coatings (crystalline carbide, diamond-like carbide (DLC) and metal dichalcogenide)	Low friction and wear-resistant applications of aircraft.
	4. Nanotube and nanoparticles (nano graphite, nano aluminum)	Electrostatic discharge, EMI shielding and low friction applications of aircraft surfaces.

Table 1. *Cont.*

Component Parts	Nanomaterials Used	Mechanical Properties
Aircraft electro-communication systems	1. Magnetic nanoparticles (iron oxide nanoparticles, i.e., Fe_2O_3 and Fe_3O_4)	High magnetic saturation, stability, biocompatibility, and interactive functions at the surface (used as data storage media).
	2. Ceramic nanoparticles (like barium strontium titanate, barium titanate)	Excellent dielectric properties (e.g., supercapacitor).
	3. MEMS (Micro-electro-mechanical system) and NEMS (nano-electromechanical system)	Controls fuel in aero-engines.

Further, aviation applications involve the expansion of sensors that can be used in absurd environmental conditions. This requires materials that encompass multifunctionality, lower maintenance and downtime expenses, reduced weight (helps in lower consumption of fuel, lower emissions, and lower launching costs), improved hazard protection, long service life, higher safety and reliability, increased functional and operational capacity. The mentioned control over the material properties using nanomaterials had enabled researchers to develop different high-quality nano propellants, ultra-lightweight materials, graphene electronics, structurally integrated energy generation and storage systems, and hierarchical integration of internal and external system and subsystems. Nanoscale sensors and devices may help in delivering cost-effective and continuous monitoring in space. An effective and advanced transportation infrastructure with an automated signal controlling through signaling to the drivers before any collision or to adjust the trafficked route can be improved utilizing the nanoelectronics. Nanomaterials-enabled lightweight, high-strength materials can be used to produce any vehicle. Figure 1 presents a timeline for the approximate years when new criteria were introduced into selecting aircraft materials.

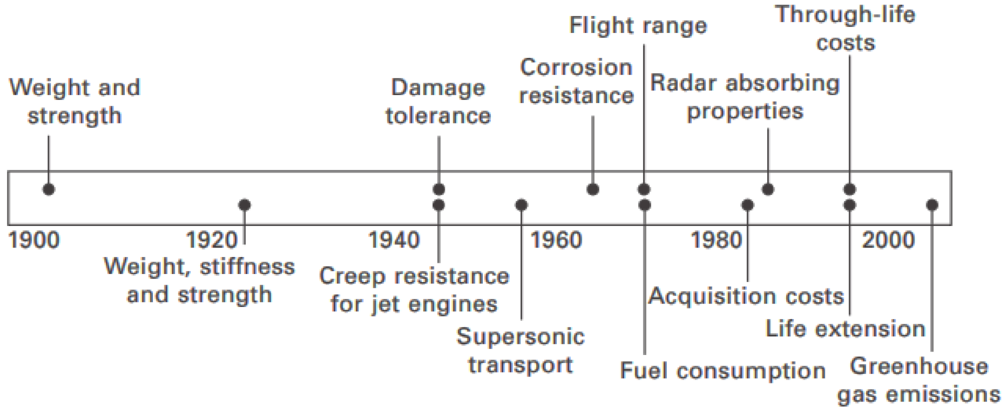

Figure 1. Historical timeline indicating when critical measures for materials selection were introduced into aircraft design [2].

3. ENMs Properties and Applications

Various nanomaterials have been used in the aviation industries in aircraft construction, such as nanocomposite polymers have been extensively used as a filler to enhance the structural properties, commonly carbon nanotubes, nanoclays, nanofibers, and graphene has been the widely chosen nanocomposites. As compared to counterparts with microscale or larger grain structure, they have substantially better properties. This is especially evident for properties critical in aerospace applications, such as yield stress, structural rigidity, resistance to corrosion, and a low density to allow for significant structural weight reductions. Moreover, nanostructured metals have been shown to not only have improved properties and can be designed to have properties that are uncharacteristic for traditionally sized materials. A nanostructured titanium-nickel alloy, for example, exhibits superelasticity and high yield strength.

Magnesium alloys are much lighter than steel or aluminum; however, due to the high reactivity of magnesium, they are compromised due to their sensitivity to corrosion. A surface coating is the most widely used solution for the control of corrosion. However, manufacturers are well documented to be carcinogenic in their favored chromium coatings. Silicon and boron oxides, as well as cobalt-phosphorous nanocrystals, are nanomaterials used as anticorrosion coatings as an alternative to chrome. Even so, an appropriate coating for aluminum, which is commonly used in aircraft structures due to its comparable performance to chromium, has yet to be developed, making it one of the sector's most significant needs. Aluminum's heterogeneous surface makes it particularly susceptible to corrosion, which is accelerated by the presence of alloying elements and precipitates. Recent studies have demonstrated magnesium nanocomposites as an interesting candidate, though this research is still in its early stages, necessitating more thorough investigation. Nanocoatings are applied to mechanical components that are subjected to high temperatures and friction wear, such as turbine blades, in addition to preventing chemical corrosion. These tribological coatings can reduce friction coefficients and improve wear resistance, resulting in increased engine efficiency and reduced fuel consumption. As a potential friction modifying agent including carbides, nitrides, metals, and various ceramics, many nanostructure and nanoscale coating materials were proposed. The following subsection will focus on two major parts in aviation: the airframe structure and aero-body and engine for their properties and applications [5–8].

3.1. Air Frame Structure

In the manufacturing of airframe structures, advanced materials and processes have led to their evolution from simple wood truss structures to today's sleek aerodynamic flying machines. Aligned with technology development, the airframe structure design required the materials to be lightweight, high toughness, high strength, corrosion resistance, easy reparability and reusability, less maintenance, and durability [9]. Figure 2 depicts the evolution of material used in airframe structure until now.

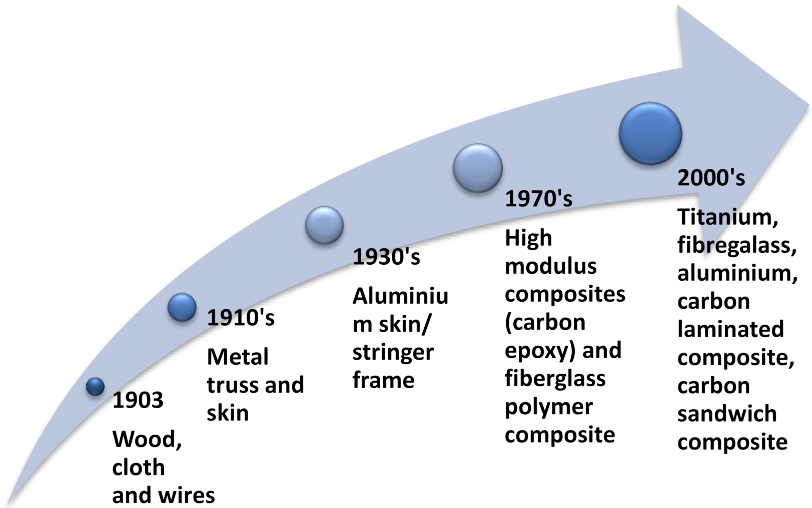

Figure 2. Evolution of materials used in the airframe structure [10–12].

The competitive existence of the aircraft construction company guarantees the exploration and exploitation of any opportunities to lower operational costs. As an increasing fuel cost has a significant impact on day-to-day running costs, researchers continuously improve the design and materials used to build the airframe structure. Based on Figure 2, it is clearly shown that the use of lighter material likes aluminum, which can lead to weight reduction, has become a critical factor in overcoming the issues of increasing fuel costs and environmental lobbying. Besides aluminum, composite materials also have gained much attention due to their advantage in mechanical properties [13]. The excellent properties of composite materials, as represented by their higher strength and stiffness per unit weight, corrosion resistance and superior fatigue for many applications, and potential for lower manufacturing costs through reduced part counts and tooling expenses, make them suited the need for aircraft designs [14].

Furthermore, composite technology continues to advance, and the advent of new types such as basalt and carbon nanotube forms is sure to accelerate and extend composite usage [15]. Based on Table 1, three types of the most composite materials used in constructing an airframe structure: carbon nanotubes (CNTs)-based polymer composites, nano-clays-reinforced polymer composites, and metal nanoparticles incorporated composites. However, the slow rate at which they are being adopted is evidence that their design, analysis, manufacturing, inspection, and repair methodologies are all in a developing stage.

3.1.1. Carbon Nanotubes (CNTs)-Based Polymer Composites

In the year 1991, Carbon nanotube was first discovered by Iijima [16]. The discovery has opened a new revolution of global research focusing on nanocomposites. However, except in a few cases, CNTs cannot be used directly in any of their bulk forms due to the inadequate translation of outstanding inherent properties of individual CNTs into its macroscopic structures. Due to that problem, the applications of CNTs usually are required the right combination with other materials in the form of alloys, blends, composites, or hybrid materials [17–25].

CNTs-based polymer composite has revolutionized materials science and technology due to the synergistic combination of flexibility, low density, and facile processing of conventional polymers with outstanding electrical properties [26]. This finding has inspired the aircraft designers with another structural material option for the airframe. The functional properties of CNTs-based polymer composites are due to their wide range of Young's modulus, high specific strength, crush resistance, and excellent thermal performance. Benefits of CNTs-based polymer composite can be seen by observing the performance and efficiency of weight reduction due to the low density of CNTs-based polymer composites [14]. Some CNTs-based polymer composites used for airframe structures are CNT/Epoxy, CNT/Polyimide, and CNT/polypropylene.

The use of CNT-based polymer composite is not only limited to airframe structure but also has been used in different fields such as electrical devices, biomedical applications, sensors, energy storage, etc. Table 2 summarizes several pieces of research that have been conducted on CNTs in different fields. In the year 2013, Lian et al. [27] have successfully produced a sensitive and selective electrochemical sensor that can confirm the presence of the element of neomycin (an aminoglycoside antibiotic). This novel imprinted electrochemical sensor was made from a modification of chitosan-silver nanoparticles (CS-SNP) and graphene-multiwall carbon nanotubes (GR-MWCNTs) composites and a MIPs film on a gold electrode.

Table 2. Previous research conducted for CNTs-based polymer composites [28].

Applications	Research Done
Sensor	- EC DNA sensor [29]
	- EC warfarin sensor [30]
	- EC routine sensor [31]
	- Vapor of chemical gas sensor [32]
	- Strain sensor [33]
	- Gas sensor [34]

Table 2. *Cont.*

Applications	Research Done
Biomedical	- Scaffold in tissue engineering [35]
	- Orthopedic implantable device [36]
	- Blood purification [37]
	- Nano-surgical needles [38]
	- Fuel empowered artificial muscles [39]
	- Joint replacement [40]
Electronic devices	- Dye sensitized solar cells [41]
	- Dry EC actuators [42]
Energy storage	- Battery electrode [43]
	- PCM thermal energy storage [44]
	- rGO/SWCNTs electrode [45]

3.1.2. Nanoclays-Reinforced Polymer Composites

Nanoclays are based on phyllosilicates, which are nanoparticles of layered mineral silicates. It has received much attention as it can be a reinforcing filler for polymers due to its ability to form a high aspect ratio and unique intercalation/exfoliation characteristics [46]. Besides that, nanoclays-reinforced polymer composites also offer a low-cost alternative to high-performance composite for many commercial applications such as aerospace, automotive, and packaging industries. The polymer-clay nanocomposite synthesis, which is formed through the dispersion in solution technique by combining the clay dispersion and polymer solution.

Nanoclays-reinforced polymer composites have been enlarging to several hybrid forms, innovative materials such as nanoclays reinforced with conductive polymer (polypyrrole (PPy), polyaniline (PANI), polythiophene (P.T.), and poly (3,4-ethylene dioxythiophene) (PEDOT), biocomposites and organoclay hybrid films with a variety of properties composite materials produced [47]. These composites offer a lighter weight with lower modified nanoclays filler content in comparison to conventionally filled systems [48]. Based on their unique properties, nanoclays-reinforced polymer composites have been widely used in many industrial applications, such as aerospace (flame retardant panels and high-performance components), automotive (gas tanks, bumpers, interior and exterior panels), construction (building sections and structural panels), chemical processes (catalysts), pharmaceutical (as carriers of drugs and penetrants), food packaging, and textiles [49]. Based on research done by Guo et al. [50], about 75–80% of these composites are implemented in the aeronautical, automotive, and packaging industries.

Due to the limitations in fossil resources and an urgent need to protect the environment, many new recent research advances are being developed to produce new generations and applications of nanoclays-reinforced polymer composites. According to Vo et al. [51], innovative bioinspired nanoclays-reinforced polymer composite material is soon expected to find their applications in various scientific and technological fields.

In the aerospace industry, the coating has played an essential role in improving the durability, reliability, and performance of various components. Besides that, it is also used for resistance on erosion, sliding, and fretting wear or to enhance the quality of surface where all of these benefits are generally used for protecting the structures and surfaces of the aircraft from harsh environments, varying temperature conditions, and high pressure. Notwithstanding, conventional aviation coatings experience the side effects of substantial mechanical, ecological, and monetary downsides, permitting new open doors for warm obstruction, ice-phobic and defensive nanocoatings in the area [52]. Figure 3 shows some of the benefits of nanocoatings onto aerospace materials.

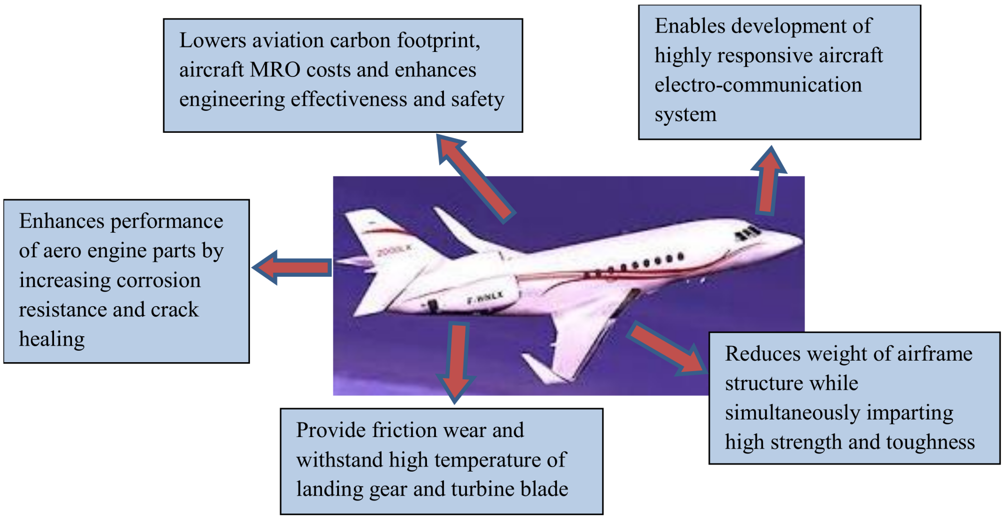

Figure 3. Benefits from nanocoatings for aerospace materials [53].

Favorable circumstances of utilizing nanocoatings in aviation incorporate decreased carbon impression, less cleaning and maintenance costs, protection against corrosion and erosion, and diminished ice accumulation. Nanocoatings are additionally proven for fuel-burn saving based on their drag reduction. In the defense industry, they have suffered from high maintenance costs because most of the coating needs to be touched-up by hand to hide the metal or other substrate material's damage. As reported by AZaNano [54], the U.S. Department of Defense needs to spend almost $10 bn per year on the corrosion-related problem. Up to $2 billion are coming from painting paint-scraping operations. They also reported that nearly 20% of armed force vehicles are out of service because of covering harm and repainting needs. In euro-engine application, nanocoatings can increase the service life of that engine because of its multilayer structure, temperature resistance, thermal shock, corrosive and erosive wear-resistant properties. Nanoparticle coatings, also known as smart coating, could enable the vehicles to identify if any eroded, scratched, or break and mend themselves, bringing about enhanced high-temperature, quality, and creep resistance.

The are several approaches related to nanocoatings technology such as ceramic coating, nanocomposite coating, sol-gel coating, layer-by-layer coating, nanoscale conversion coatings, etc. It has been found from the literature review that some of the materials like SiC-particle-reinforced alumina, crystalline carbide, diamond-like carbide (DLC), metal dichalcogenide, nano graphite, and nano aluminum are being used as nanocoating in the aerospace industry. SiC-particle-reinforced alumina is one example of ceramic coating. It can provide high-performance oxide layers on metal and alloys to solve corrosion, friction, heat, insulation, and wear problems [55]. Besides that, this material has been approved to produce high-temperature structural materials based on their excellent thermo-mechanical properties. Cui et al. [56] have researched nano-SiC coating formed on Al surface by using a laser shock processing technique where they found that by applying this technique, a nano-SiC coating can give a superior microhardness (almost 40.5% of increment compared to original hardness) over the Al surface. This result happened because the nano-SiC particles are greatly hammered into the Al substrate under a high-pressure shock wave induced by the process used that increased the Al substrate's hardness. In the other research done by Musthafa [57], Al_2O_3 nano-ceramic material with 200 μm thickness using the plasma spray coating method has been applied for the thermal barrier coating for the diesel engine. The experiment was done by running a diesel undercoated and uncoated engine where both results were compared. The results show that the coated engine can increase the engine power, decrease the specific fuel consumption, and improve exhaust gas emissions (except NOX) compared to the uncoated engine.

Other than the ceramic coating, nanocomposite coating such as crystalline carbide, diamond-like carbide (DLC), and metal di-chalcogenide is also a popular coating material used in the aerospace industry. Nanocomposite coating is produced by mixing two or more nanomaterials to enhance the materials' physical, chemical, and physicochemical properties. These materials are being used in the aerospace industry and offer a great application in other areas such as electronics, biomedical implants, automotive, energy conversion, and many others [58]. In recent research by Bayer et al. [59], they have developed a superhydrophobic coating to prevent aerodynamic insect fouling during take-off, climb, and landing, increasing drag and fuel consumption for the laminar flow surfaces. The experiment found that this coating can maintain negligible insect residue levels after 100 high-speed (50 m/s) insect impact events produced in a wind tunnel. They also address that this coating exhibited worthy dimensions of wear abrasion and substrate adhesion obstruction against pencil hardness, dry/wet scribed tape strip adhesion, and 17.5 kPa Taber straight abrader tests. Basiru et al. [60] investigated silicone-modified epoxy polymeric matrix reinforced with 2 wt. % SiO_2, TiO_2, and $TiSiO_4$ nanoparticles were used to protect the surface from corrosion. Experiments were done under three different environmental conditions (static, U.V., and dynamic) with submersion in 3.5 wt. % NaCl solution was done utilizing electrochemical impedance spectroscopy (EIS) testing to see the degradation level. The results show that the coating systems with added SiO_2 demonstrated the most pronounced enhancement of hydrophobicity, which can be ascribed to the low surface vitality of silicone of 22 mN/m. The EIS results also confirmed the nanoparticles' capacity to upgrade the hindrance properties and enhance the corrosion protection execution of the polymeric matrix.

Furthermore, Fan et al. [61] have covered that diamond-like carbon (DLC) films can provide low friction and wear due to the decreasing amount in abrasion, shear, and adhesion excellent mechanical properties. To optimize the DLC coatings for specific applications under the challenging space condition, they have manufactured and efficiently researched DLC-based solid-fluid cooperative energy greasing up frameworks. These frameworks give excellent tribological properties and high versatile capacities to the space condition, which is vital for the prolonged haul activity of robust and precise moving systems in space.

Nanocoatings are not only used to protect the surface from damage or rust, but are also used to prevent the body from freezing at high altitude. A proprietary technology based on resistive heating coating has been used to protect the aircraft from getting covered by ice. One of the materials that have been identified to overcome this problem is by using graphene. Introduced in 2004 by Konstantin Novoselov dan Andre Geim, graphene is the two-dimensional material that can increase aircraft performance, fuel efficiency, and cost. This material is multiple times stronger than the most substantial steel, with an atomic thickness of around 0.345 mm. Besides that, graphene can conduct heat and electricity in an acceptable condition. Research has been performed on the anti-icing/de-icing topic by using a mixture of graphene. Redondo et al. [62] used epoxy coating mixed with graphene nanoplatelets (GNP) with average thickness near 200 μm have been made on glass fiber cover substrate. The use of GNP in the epoxy coating can increase the electrical conductivity of the coating. With a connected voltage of 750–800 V, they figure out that the epoxy coatings doped with 8 to 12 wt. % of GNP are reasonable as anti-icing frameworks at −15 °C, apropos evading ice formation.

Moreover, higher than 12 wt. % of GNP substance are required if the framework is to be utilized as a de-icing framework, for melting the ice up to −30 °C. They concluded that the covering doped with the most astounding GNP content introduced increasingly proficient warming because of its higher electrical conductivity and higher transported electrical flow.

Furthermore, Karim et al. [63] have made a highly conductive graphene-based glass fiber roving dedicated for the use of de-icing applications. They have coated the glass fiber roving with a graphene-based solution using a dip-dry-cure technique, as shown in Figure 4. The graphene-based glass shows a low resistance from their experiments, which is around 1.7 $\Omega cm^{-1,}$ and effective warming to an ideal temperature at lower control utilization. They found that the de-icing test demonstrates proficient expulsion ice from graphene-based composite.

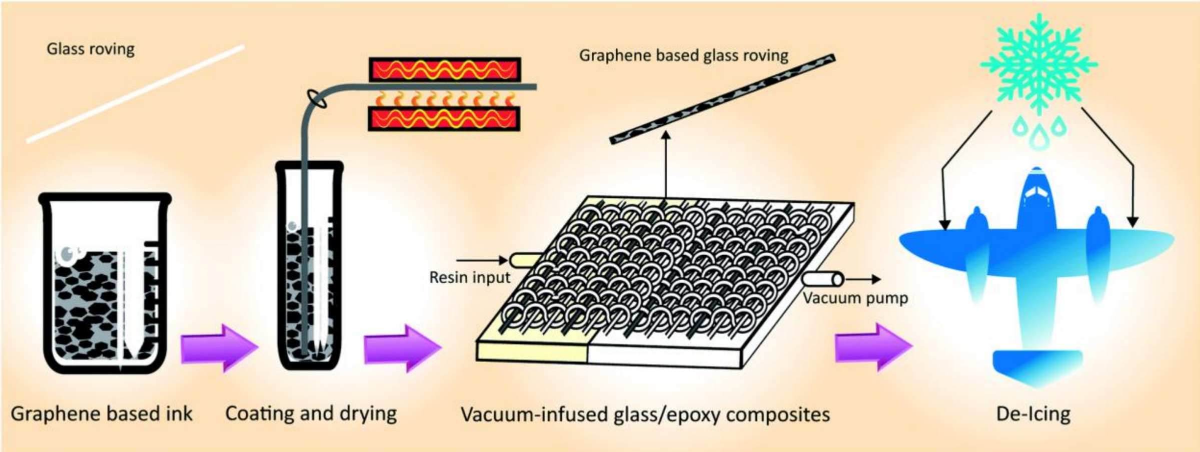

Figure 4. A dip-dry-cure technique for manufacturing graphene-based glass/epoxy composites for de-icing applications [63].

Other than graphene, Zhoa et al. [64] have developed the anti-icing coating for fiber-reinforced plastic (FRP) that is commonly used as aircraft wings and wind turbines (refer Figure 5). The new multi-layered coating has been developed with the combination of fronted electric heating coating and top with superhydrophobic coating. From the anti-icing experiment conducted, it was proved that the thin water layer resulted from electric heating was significantly reduces the ice adhesive force on FRP material. In other research done by Khadak et al. [65], they found that de-icing capabilities of carbon-fiber-reinforced composite could be increased by applying a double layer superhydrophobic coatings system. The surface coated with this superhydrophobic coating will tend to have a rough and waxy surface that shows a contact point of more than 150°. Promising contact points above 150° were uncovered that in the wake of playing out a de-icing test on different occasions, the examples gave fantastic de-icing abilities.

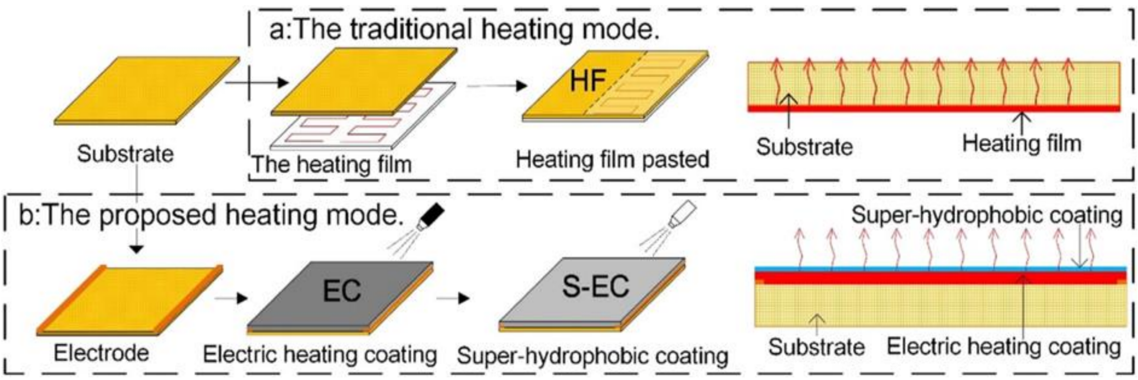

Figure 5. Schematic of the fabrication process and the heating mode of the samples (**a**) H.F. and (**b**) S-EC. (Reported from [64] with permission; Copyright 2018 Elsevier B.V.).

On the other hand, thermal barrier coatings also have gained widespread attention due to their ability to accommodate better thermal cycle life, decreased tendency for sintering in grained columnar structures, and lessen thermal conductivity [65–67]. Also, thermal barrier coatings can function as temperature sensors or high-temperature electronics and remote transmitters [67]. Nanoparticles additionally can enhance the fire impending execution of polymeric materials [68]. The established thermal barrier and fire retardant nanocoatings method is plasma spray coating [69–71]. For the plasma spraying process, particles with a size range 10–100 µm are injected into the plasma jet and instantly melted and accelerated to yield a flow of molten particles that are projected onto the substrate. The most crucial parameter in this process is to make sure the particle injected into the jet is completely melted. The particle will bounce off from the substrate if the particle is not melted completely [71]. On impact, the liquid droplet flattens to form a disc, the detailed shape of which is determined by the surface tension, density, viscosity, and velocity of the liquid droplet [72]. This method is facing new challenges when applying nanosized powder as feedstock to generate nanostructured coatings for antifouling and anticorrosion [73–75]. The main challenge is that individual nanoparticles cannot be thermally sprayed because of their low mass and the resultant inability to be carried in a moving gas stream and deposited on a substrate. To overcome this restriction, Shaw et al. [76] suggested that it is necessary to reconstitute individual nanoparticles into spherical micrometer-meter sized granules.

The second challenge is to retain grain size at the nanometer regime in the coating, which may be achievable through using Al_2O_3-TiO_2 powder feedstock. McPherson [75] found that if the partly melted particle has high enough viscosity and impact velocity during thermal spray is not too high, there is a chance of this particle incorporated into the coating during the thermal spraying process. Shaw et al. [76] implemented short exposure to the plasma flame, and the TiO_2 particles will be melted. At the same time, the Al_2O_3 nanograins will remain unmelted due to melting point different for both materials, as shown in Figure 6. This study concludes that nanostructured Al_2O_3-TiO_2 powders have been successfully reconstituted into thermal sprayable feedstock. Besides all the research mentioned above, Table 3 below summarizes other investigations done in the last five years.

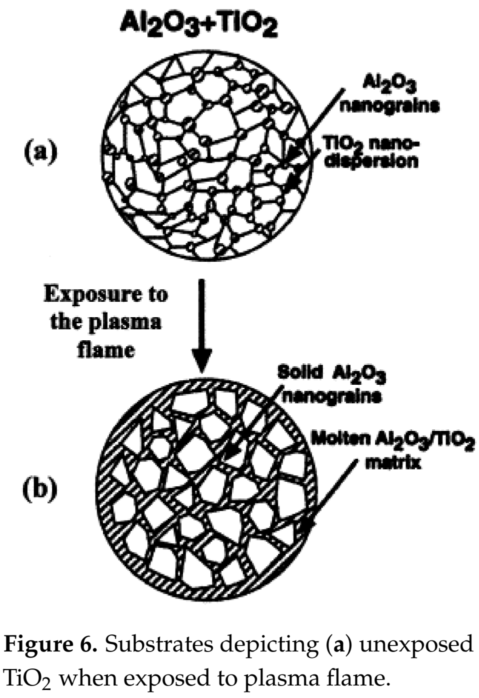

Figure 6. Substrates depicting (**a**) unexposed Al_2O_3-TiO_2 nanograins and (**b**) morphology of Al_2O_3-TiO_2 when exposed to plasma flame.

Table 3. Previous research work on nanocoatings for aerospace application.

Researchers	Year	Findings
Sun et al. [66]	2015	- Used cubic Fe2O3 NPs as nanofiller for epoxy matrix coating. - The interaction between Fe2O3 NPs and the epoxy matrix has improved the mechanical property by 1.5 times the tensile strength and two times better for fracture toughness.
Civcisa & Leemet [67]	2015	- Comparison of 3D surface roughness parameters between Ti-N coating and Ti-Al-N coating for the use of airplane blades. - Ti-Al-N coating gives smoother surface roughness compared to Ti-N coating.
Roy et al. [68]	2016	- Developed new AlPO4-C composite coating for Ni-based superalloy substrates using dip coating and spray coating techniques. - Improved the coating's emissivity, which can prevent the oxidation on the base substrates at elevated temperature.
Huan et al. [69]	2017	- Tested the NiCo nanocoatings on aerospace aluminum alloy using non-contact photo-thermo-mechanical radiometry (PTMR). - NiCo coating can improve the mechanical properties of a coated material by strengthening the parts and protecting the defective substrate.
Delfini et al. [70]	2017	- They studied the effects of erosion by atomic oxygen onto carbon nanostructure as base material and carbon fiber as a coating material. - The disordered carbon deposit has seen an exacerbation, and improvement was accomplished by the high return carbon monofilaments deposition.
Ng et. al. [71]	2018	- A co-polymer coating and wax formulation generated hydrophobic and heterogeneous surface onto the aerospace P.U. topcoat. - The ice adhesion strength can reduce up to 47% and save up to 70% in energy required to remove the ice from the coating surface.
Gul et al. [72]	2018	- Observed that epoxy nanocomposites give a better corrosion resistance compared to pristine epoxy samples.
Fazli-Shokouhi et al. [73]	2019	- For anticorrosion, epoxy-12 wt. % PANI-GON coating revealed the highest anticorrosion level - For antifouling, epoxy-6 and 12 wt. % PANI-GON coatings show the most efficient antifouling level.
Iribarren et al. [74]	2019	- They analyzed the effect of different electrospinning deposition parameters on coating properties. - Electrospinning technique can enhance the surface resistance against localized corrosion by using the PVC-ZnO nanocomposite coating.

4. ENMs in Developing Aerospace-Focused Antiviral Films/Coatings

One of the biggest risks to human health since the influenza pandemic of 1918 has been the COVID-19 viral outbreak, which has significantly increased the demand for antiviral vaccines. Considering the nature of the COVID-19 virus, i.e., it can spread from human to human and from various surfaces touched or sneezed by the infected person. Therefore, the surfaces with high contamination must be sanitized/disinfected. However, current disinfectants are based primarily on substances such as toxic sodium hypochlorite (bleach) or alcohol, all of which offer only an interim measure before the next virus exposure [77]. To complement the current scenario and future aspects of fighting with present and future viruses, it is necessary to establish novel and long-term strategies that can save human lives. Besides the importance of minimizing and preventing the pandemic, it is also essential to raise the next generation of antiviral techniques that are as robust as possible and display a broad spectrum of antiviral activity.

The aviation sector has become one of the highest suffered sectors of COVID-19 infection. Recent forecasts published in July 2020 by International Civil Aviation Organization (ICAO) suggest that the potential effect of COVID-19 on global projected passenger traffic for the fiscal year 2020 will be as follows from the benchmark (business as normal, originally intended) [78]:

- The total reduction varies from 42% to 52% of the seats provided by airlines.
- A net drop of 2369 to 2947 million passengers.
- Approximately USD 316 to 390 billion possible loss of net operating profit of airlines.

This effect depends on the length and severity of the outbreak and control steps, the extent of public confidence in airline travel, economic circumstances, etc. Therefore, to combat the effect of the COVID-19 virus and be prepared for future virus attacks, sustainable and robust research is required to develop antiviral nanomaterials and coatings to protect the airplanes' interior and to safeguard the passenger's trust. Doremalen et al. [79] examined surface survival of COVID-19. They observed that the COVID-19 virus can stay on copper in an infectious state for 4 h, on cardboard for up to 24 h, and on plastic and stainless surfaces for two to three days under the specified experimental conditions. Hence, antimicrobial treatment in urban spaces should be a significant preventive step to prevent COVID-19 from spreading from these materials.

Antimicrobial/antibacterial coatings are often organic compounds or are bioactive made up of polymer/chemically synthesized polymer or nanoparticles capable of killing or inhibiting infective bacteria, fungi, and viruses' growth [80]. The microbial membrane crosses and impairs the metabolic path, leading to changes in membrane structures and functions, to avoid binding microbes to the surface. They induce oxidative stress within the microbes that lead to electrolyte imbalance, protein damage, and antioxidant enzymes that lead to gene expression changes and eventually cause microbes to die. Silver, copper, and zinc hybrid antimicrobial coating has strong virucidal effects on various viruses such as HIV-1, human herpesvirus 1, H1N1 influenza and Type 2 dengue viruses, making them excellent virucides applicable to rising surfaces [81]. Several studies have noticed that different nanostructures/particles are effective against enveloped viruses in antiviral therapy, some of which are listed in Table 4 [77,81–86]. In novel antiviral therapy, various metal nanostructures such as zinc oxide, tin oxide nanowires, and zinc oxide tetrapod are commonly used. Similarly, nanomaterials of silver, gold, silicon have been studied for their strong antiviral efficacy. They discourage viruses from entering by imitating cell receptors or suppressing gene expression replication and viral assembly [86].

Table 4. Virucidal effects of antimicrobial nanomaterials and coatings.

Authors and Year	Virus Designated by WHO	Antimicrobial Nanomaterials and Coatings	Application
Porgador et al. [77]	Covid-19	Nanomaterials of antiviral and antibacterial metal ions (copper) and polymers	Avoid contamination and prevent virus entry
Lun et al. [87]	Covid-19	Multilevel antimicrobial polymer	Avoid contamination and prevent virus entry up to 90 days on various surfaces of different materials.
Hodek et al. [81]	Spanish Flu (Influenza)	Coatings prepared by combinations of silver, copper, and zinc nanomaterials	Inhibit viral attachment to host plasma membrane
Trigilio et al. [82]	Herpes simplex virus type 1 (HSV-1)	Coatings prepared by tin oxide nanowires	Preventing virus entry into host cells
Speshock et al. [83]	Tacaribe virus (TCRV)	Polysaccharide-coated silver nanoparticles	It inactivates the infective virus before reaching the host cell
Lu et al. [84]	Hepatitis B virus (HBV)	Silver nanomaterials	Interfere with viral DNA replication and binding
Sun et al. [85]	Respiratory syncytial virus Herpes simplex virus type 2 (SV-2)	PVP-coated silver nanoparticles zinc oxide tetrapod nanoparticles (ZOTEN)	Viral binding to host cell interferes. Join with virions, and avoid cell entry

In attempts to counter the COVID-19 epidemic, HKUST, China researchers have developed Multilevel Antimicrobial Polymer (MAP-1), which has been shown to be capable of inactivating up to 99.9% of extremely contagious viruses like measles, mumps, and rubella. MAP-1 coating surface mobilities aggressively damages the microbial shell and biomolecules, prohibiting microorganisms from contact. A unique combination of antimicrobial polymers also inhibits the adhesion of microbial on surfaces. They reported that this MAP-1 coating has excellent resistance for an adequate time of up to 90 days and is engineered for use on various surfaces, including steel, asphalt, wood, glass, plastics, fabrics, leathers, and textiles without altering the look and touchy feel of the materials. The coating has been proved to be non-toxic and safe for the skin and the environment, as per the Disinfection Technical Standard issued by the National Health Commission in Mainland China [87–92]. Recently, scientists from Ben-Gurion University of Negev (Be'er Sheva, Israel) have developed new surface coating, which contains nanomaterials comprising safe metal ions and antiviral and antimicrobial polymers. These metals can be lethal to viruses and bacteria, even in small quantities and also not harmful to people. The researchers have proven the impact on infectivity of lentiviruses belonging to the HIV family in human cells of surfaces coated with nanoparticles of many metals. Their findings show that copper-coated surfaces strongly block the viral cell infection [77]. Rai et al. [80] carried out an analysis on metallic nanoparticles' antibacterial, antifungal, and antiviral capacity. The authors indicate the use, either with or without surface change, of metallic nanoparticles, particularly silver nanoparticles and capped nanoparticles (glutathione-Ag2S clusters) [93] as a powerful and large range antiviral agent. However, these nanoparticles have largely unexplored their antiviral activity. Further detailed study on use of various nanomaterials as antimicrobial coatings are presented in [93] and Figure 7 provides a schematic showing the functioning of antimicrobial material on COVID-19 virus to prevent its transmission.

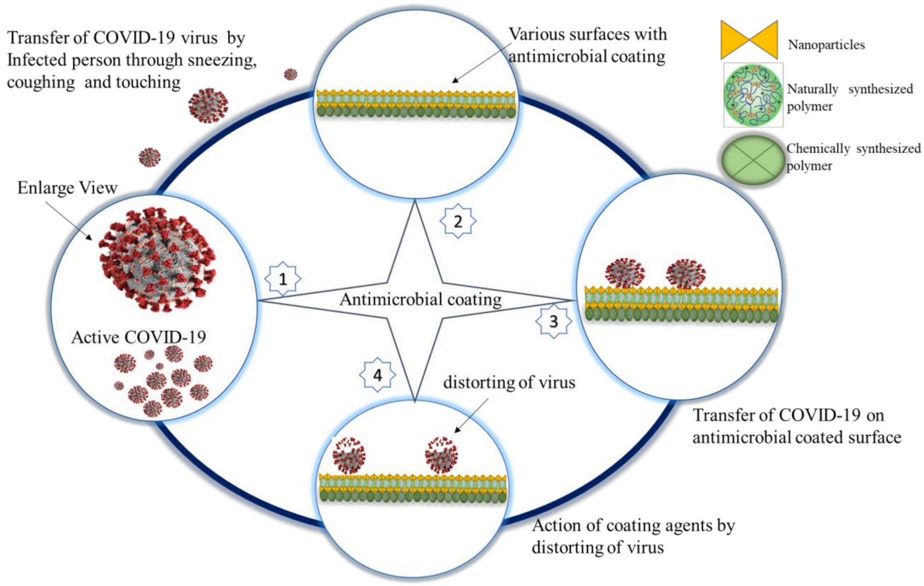

Figure 7. Schematic display of functioning of antimicrobial material on COVID-19 virus.

5. ENMs Synthesis Techniques

Nanomaterials (NMs) synthesis techniques can be divided into two basic categories, as shown in Figure 8. The first category includes *bottom-up* or *build-up* approaches which begin with atoms and molecules at the bottom level, which react under certain chemical and physical circumstances to form nanostructures. The second category includes *step-down* or *break-down* approaches which begin with bulk material from the top, which is subsequently reduced into nanostructures by way of (i) physical; (ii) chemical; and (iii) mechanical processes. The above-mentioned methods can be subdivided into different mechanisms depending on the requirements, but the operating principle remains the same, the Tables 5 and 6 provides a comparison of the three aforementioned mechanisms. Solvents and hard chemicals in fluid/gas were commonly employed in the *chemical synthesis of NMs*, which are produced by NM. This process results in an easy and non-laborious working environment for the bulk generation. Although the processing of bulk materials in the form of small particles is done by mechanical processing, compared to other processes the process is less complicated; uncontaminated particles can be generated [88]. In contrast, physical processes can produce controlled particle size and can produce pure NMs.

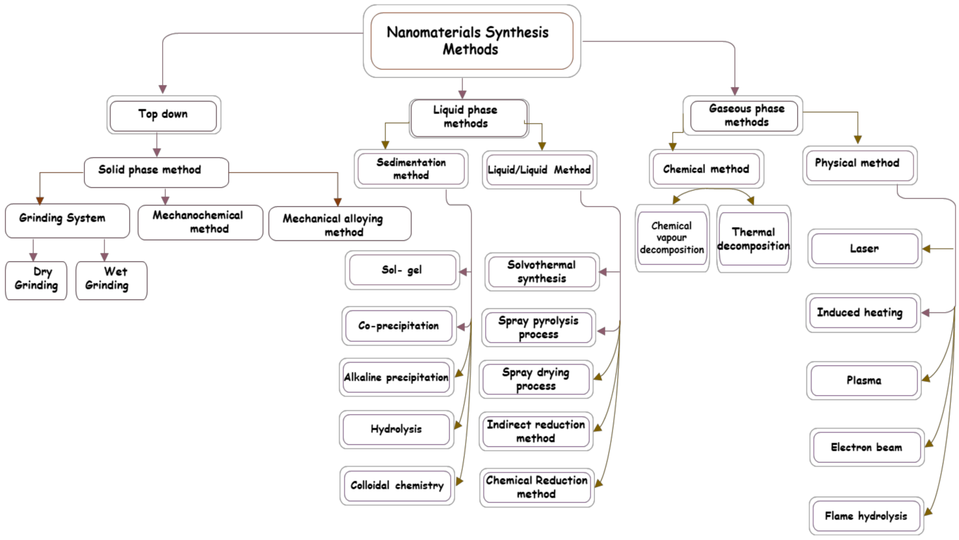

Figure 8. Different methods for generation of nanomaterials.

Table 5. Comparison of nanomaterials synthesis methods [89,90].

Type of Processes	Cost	Time	Oxidation	Waste Material
Chemical	High	High	High	High
Mechanical	High	High	Low	High
Physical	High	High	Low	Low

Table 6. Comparison of different nanomaterials synthesis process mechanism [89,90].

Physical Processes	Chemical Processes	Mechanical Processes
Physical vapor deposition, laser ablation, sputter deposition, electric arc deposition, ion implantation etc.	Sol-Gel, electrodeposition, colloidal methods, water-oil micro emulsions method, hydrothermal synthesis etc.	Attrition ball mill; vibrating ball mill; high energy ball mill; vibrator etc.
Advantages: Fewer losses compare with other processes, chemical-free process,	**Advantages**: Easy, less time consuming, large quantities of material can be obtaining, variety of size and shape, self-assembly or patterning possible	**Advantages**: Pure NM chemical-free process
Limitations: Time-consuming, required high-class setup, control over the process is a typical task, and high skilled labor is required.	**Limitations**: High cost, high chemical waste contaminated NMs, hazardous for environment and human.	**Limitations**: More space required; high energy required; the non-uniform shape of particles; phase change possibilities.

Methods included in the *step-down* category are also referred to as *grain refining* methods in which surface energy of the materials increases, which increase aggregation of the materials. Therefore, it is difficult to obtain material sizes of less than 3 μm by grain refining because of condensation of small materials also takes place simultaneously with pulverization. Grinding, mechanical-chemical methods, and mechanical alloying are methods of nano-materials generation that belong to this category. *Grinding* can be further sub-divided into two types, namely wet grinding and dry grinding. In the *dry grinding* method, the solid substance is ground using a shock, a compression, or by friction, using such popular methods as a jet mill, a hammer mill, a shearing mill, a roller mill, shock shearing mill, ball mill. On the other side, a rigid substrate is wetly broken by a ball molding or a vibrational ball mill, planetary ball mill, centrifugal watermill, or wet jet mill in wet grinding process. Highly distributed nanomaterials can be obtained by means of a wet grinding process since it is possible to avoid condensation of nanomaterials produced such that it is not feasible for dry grinding.

The *bottom-up approaches* can be further divided into two groups, namely (i) gaseous phase methods; and (ii) liquid phase methods. *Gaseous phase methods* include: (a) chemical methods involving a chemical reaction such as chemical vapor decomposition (CVD) and thermal deposition; and (b) physical vapor decomposition (PVD) methods which involve evaporation of liquid or solid material using either laser, plasma, electron beam, induction heating or flame hydrolysis and rapid cooling of the evaporated material yielding the desired nanomaterials. *Liquid phase methods* have been the primary methods for the generation of nanomaterials for many years. They can be further subdivided into two types, i.e., (i) liquid/liquid methods: which include chemical reduction method, indirect reduction method, spray pyrolysis, spray drying and solvothermal synthesis; and (ii) sedimentation methods: which include the sol-gel method, alkaline precipitation, co-precipitation, hydrolysis, and colloidal chemistry method. The gaseous phase methods prevent the severity of nanomaterial organic impurity compared to the liquid phase processes, but they require the use of complex, low efficiency, and high costs vacuum devices. The *CVD* method can produce ultra-fine materials of size less than 1 μm utilizing gaseous phase chemical reaction. Nanomaterials from 10 to 100 nm can be generated by careful reaction control. The CVD process involves heating source such as a chemical fire, a plasma process, laser, or an electric furnace to perform the high-temperature chemical reaction. In the production of metal oxide or other types of materials, the *thermal decomposition* method was particularly useful as an industrial preferable synthesis method. A typical example of a liquid/liquid method is the *chemical reduction* of the metal ions whose primary benefit is the easy manufacturing of materials of various forms, such as nanorods, nanofilms, and nanofillers. By changing the reducing agent, the dispersing agent, the reaction temperature, and time it is possible to alter the shape and the size of the nanomaterials. It reduces the metal ions to their zero oxidation levels through chemical reduction. The method uses uncomplicated tools or instruments and can produce large amounts of nanomaterials for a limited period of time at low cost. Metal oxide nanomaterials were manufactured by the sole-gel process extensively. The hydrolysis, accompanied by polycondensation to a gel, converts a solution of a metal oxide into a sol. The wet process ensures that the nanomaterials are dispersed in comparison with the dry techniques [88,89]. Besides that, if the subsequent nanomaterials are dried, the aggregation of the materials will soon follow. In this case, it is possible to re-disperse the solid phase method using the procedure.

Some features are common to all the methods of generation of nanomaterials, i.e., synthesis of nanomaterials require the use of a tools or methods that fulfils the following condition [88]:

- Control over NMs volume, size, form, crystalline structure, composition and distribution.
- Improved nanomaterial cleanliness.
- Stability in physical characteristics and structures.
- Higher replicability and aggregation control.

- Large scale production and lower cost.

6. Advantages and Limitations of ENMs in Aviation

ENMs promises the development of multifunctional materials which will help construct and keep aircraft, spacecraft and ships light, safer, smarter, and more effective. ENMs also enable many ways of improving transport infrastructure. The following are few worth mentioning advantages and limitations of ENMs in aviation:

- As discussed above in the paper that the ENMs include structural parts of polymers nano-composites; extreme powered rechargeable batteries, thermoelectrical materials for control of temperature; lower rolling tires; high efficacy and cost-effective sensors and electronics. In terms of improvement in high-performance, resilience and durability of aviation infrastructure ENMs made of aluminum, steel, copper, silicon and respective recycled formulations offer a great promise [7–12,91].
- Another common issue in aerospace vehicles is the surface deterioration of coatings because they are exposed to moisture, sunlight, and oxygen. By adding different ENMs, the surface degradation can be reduced while retaining the necessary properties of the layer. With several wall-mounted CNT, TiO2, SiO2 ENMs, and graphene, surface cracks decrease, UV degradation decreases and increases its lifespan. Inclusion of nanoclay to aircraft paints provides high fire retardant and also enables scratch-resistant properties [7–11,91].
- Aircraft engines are rendered excellent by including nanoclay and ZrO ENMs in the composite associated with Y2O3. The coating with nanofilms of engine parts facilitates self-cleaning and reduces friction. Comprehensive readings of different pressure and temperature are provided by Nanosensors and NEMS [7,91].
- For the protection of critical aircraft components from electromagnetics, nanomaterials like single-walled CNTs can be used.

  Limitations:

- Although there are numerous advantages of nanocoatings compared to traditional coatings, some issues require further development. Main problems in nanocoatings are nanoparticles scattering and stability, pigments can lose color and ultra-fine particle hardness [91].

7. Conclusions and Perspective

The use of novel materials, nanosensors, and miniaturized robots may enhance spacecraft performance. Using nanotechnology, ultra-small sensors, power sources, and even life support systems, communication, navigation, thermal protection, and propulsion systems can be developed with very tight tolerances, less weight, volume, and energy consumption. It is projected that replacing traditional aviation materials (such as composites and alloys) to innovative composites originating from lightweight, high resistance, and resilient nanomaterials may minimize the spacecraft weight by 30%. The microbial and antiviral nanomaterials coatings may help fight deadly viruses such as COVID-19 and other future viruses. Although, the comprehension and optimization of production parameters including coating thickness, surface morphology, functionality, and outstanding reliability are important for the commercial exploitation of ENMs with antiviral properties as coating materials. Over the years research has enabled researchers with a better insight of the underlying mechanisms in nanomaterial formulation, their inherent characteristics of improved surface area and quantum effects, and it still contributes to the development of sophisticated analytical techniques for their analysis and comprehensive tailor-made synthesis. Also, a strong need of understanding the mechanism of coatings with anti-viral ENMs in vitro and in vivo conditions is also important in the long term. Nonetheless, besides the benefits that nanotechnology provides to humanity, this also has detrimental effects that are not yet known to the society and the environment, since the quantum physics that govern the interactions of nanomaterials with certain other substances often makes it difficult to anticipate their toxicological behaviors.

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