Advances in Nanotechnology and Nanoparticles in the 21st Century – An Overview

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Abstract

Nanotechnology is the branch of science and engineering that involves the study of particles at a dimension of as low as between 1 and 100 nanometers. These fine particles, referred to as nanoparticles, mostly are undetectable by human eyeand they find wide application in various fields ranging from drug delivery and chemotherapy, magnetism, optics, because of their remarkable traits and endearing properties they possess.This study therefore reviews the recent advancements in nanotechnology and nanoparticles. It dealt with different approaches in synthesis nanoparticles. The physicochemical properties and classifications of nanoparticleswere highlighted in the review.

Keywords
Nanotechnology, Nanoparticles, Nano, Materials, Century, Advance

1. Introduction
Nanotechnology is among the most exciting and fast-moving scientific disciplines today. It is essentially a modern scientific discipline that is continually evolving as academic and commercial interest grows and as novel research is presented to the world of science(Pal *et al.*, 2011). The simplest definition of nanotechnology is "technology on the nanoscale" (Nasrollahzadeh *et al.*, 2019). Nevertheless, the definition of the nanoscale is indispensable for the definition of nanotechnology, which is a scale ranging between 1 to 100 nanometres (nm) (Ramsden, 2016). The prefix of the term "nanotechnology" is derived from the ancient Greek etymon "Nanos" and the Latin etymon "Nanus", signifying dwarf or extremely small. By convention in the International System Units (SI), nano refers to 10^{-9} power or one-billionth of a meter (Salman-Ali, 2020). In these terms, it refers to a nanometre, which is on the scale of the diameter of an atom (Wani, 2017). Nanotechnology involvestiny materials that are undetectable to neither the naked eye or a traditional light microscope (Ramsden, 2016). "Nanometre" was a concept that was first proposed by Richard Adolf Zsigmondy. He proposed the term nanometre for explicitly characterizing and measuring the size of particles such as colloids with the use of a microscope (Ramsden, 2016). Richard Feynman (oftentimes regarded to as the

progenitor of nanotechnology due to his first mention of the term), during a conference gave a lecture in 1959 (Bayda *et al.*, 2020), during which he described how scientists could precisely manipulate and control individual atoms and molecules. In his words, he said, "but I am not afraid to consider the ultimate question as to whether, in the great future, we can place atoms the way we want; the very atoms, all the way down!". Feynman's lecture is viewed as the first academic lecture to deal with a central tenet of nanotechnology through molecular manufacturing (i.e., direct manipulation of individual atoms). It is referred to as the first step of the nanotechnological paradigm (Yadav, 2018).

2. Brief History of Nanotechnology

In 1974, 15 years after Feynman's lecture, the term "nanotechnology" was coined and introduced into the scientific world for the first time by Professor Norio Taniguchi – a Japanese scientist, in his attempt to describe the process of semiconductors and ion beam milling on the order of a nanometre during an international conference on Industrial Production in Tokyo (Nasrollahzadeh*et al.*,2019; Kargozar and Mozafari, 2018; Malhotra and Ali, 2018). Taniguchi stated that nanotechnology comprised processing steps of dissociation, merging and material deformation, giving nanotechnology a technical definition (Malhotra and Ali, 2018). However, in 1981, with the invention of the Scanning Tunnelling Microscope (STM) by Gerd Binning and Heinrich Rohrer, an individual atom could be identified (Deshpande and Meghe, 2014). This period is referred to as the "golden era" of nanotechnology, which was advanced further by discovering Buckminsterfullerene C_{60} (buckyballs) by Harry Kroto, Richard Smalley, and Robert Curl (Bayda *et al.*, 2020). The use of the word "nanotechnology" coined by Taniguchi's and the concepts put forward by Feynman, Eric Drexler of Massachusetts Institute of Technology (MIT) developed them as a building block in presenting his vision on molecular manufacturing in his now infamous book, "Engines of Creation: The Coming Era of Nanotechnology" published in 1986 (Anne-claire *et al.*, 2015). This book described nanotechnology as engineering on the billionth of a metre scale, giving it a commercial definition (Bayda *et al.*, 2020). Directly after his book's publication, Drexler founded the Foresight Institute to raise public knowledge and understanding of nanotechnology concepts and implications (Bozsaky, 2015). With many important discoveries and inventions from the late 1980s to the early 1990s, an essential influence on nanotechnology's further development was created (Leon, 2019). As a result, significant improvements have been made in nanotechnology research and design, and the number of publications on nanotechnology has increased.

2.1 Current Use and Future of Nanotechnology

Nanotechnology is an emerging science that is expected to have exponential growth. According to scientists, nanotechnology is predicted to significantly contribute to economic growth and job creation (Bozsaky, 2015). Extensive research and developmental studies into nanotechnology have highlighted that this technology possesses limitless potential over a diversified range of technological areas as well as risks (Hull, 2018). In the food and cosmetic industries, nanotechnology has played an integral part in bioavailability, production, packaging, and product shelf life due to the use of nanomaterials (Zaib and Iqbal, 2019). Nano-sensors like zinc quantum dots have been developed to append antimicrobial activity against food-borne bacteria, ensuring food quality and safety (Gour *et al.*, 2019). Nanotechnology has also profoundly impacted environmental remediation by using engineered nanomaterials to pursue a pollution-free planet (Oyewo *et al*., 2018). In biotechnology and medical and research, nanotechnology has been widely studied for its potential benefits. For instance, medical tools (imaging probes, diagnostic biosensors, and drug delivery systems) made from nanoparticles are used to treat several diseases (neurodegenerative, cardiovascular, cancer, and diabetes), making medical procedures cheaper, safer, portable and more comfortable to administer (Kouhi, 2019).

Today, nanotechnology is widely used and impacts daily human lives with diverse benefits. Nevertheless, due to widespread exposure of humans to nanoparticles, there is a significant concern about their cycle's potential health and environmental risks (Hull, 2018). These concerns resulted in further scientific disciplines, including nanotoxicology and nanomedicine(Sikkander and Razak, 2021). Nanotoxicology studies potential hazardous effects of nanoparticles on humans and the environment, including preventing and ameliorating such hazardous effects (Muthuraman and Kaur, 2017). Nanomedicine, the new branch of medical science, was developed to study the benefits and risks of nanomaterials being utilised in medicine and medical devices; it includes subsectors such as medical diagnosis, bio-imaging, and tissue engineering (Anik *et al.*, 2020; Asha, 2020). Enhanced drug delivery, early detection of circulating cancer cells and and reduced inflammation are some of the benefits of medical nanomaterials. Unfortunately, there still exist the possibilitythat nanomaterials could pose serious health challenges to humans because of the absence of reliable toxicity data (Khan, 2015).

2.2 Nanomaterials and Nanoparticles

Nanoparticles (NPs) are a category of materials with distinctly different properties from their corresponding molecular and bulk equivalents (Karak, 2019). These particles are recognised as the building blocks for nanotechnology and are referred to as particles with at least one dimension less than 100 nm(Asha, 2020). NPs can, therefore, be defined as ultra-dispersed solid particles with supramolecular structures having a sub-micrometric size in the scale covering 1 to 100 nm (Ankathil *et al.*, 2017). NPs (figure 1) could also be definedas a nano-objectin which all three external dimensions exists in the nanoscale, such that the term "nanorod" or "nanoplate" are used in place of NPs when the lengths of the longest and shortest axes of the nano-object vary significantly (usually by more than three times) (Wyser *et al.*, 2016). However, a more technical but wider-ranging definition of nanomaterials was endorsed by European Union (EU) in 2011, where NP was defined "as a natural or manufactured material which contains particles, in an unbound state or as an agglomerate or an aggregate and where, for 50 per cent or more of the particles in the number size distribution, one or more external dimensions is in size range 1 to 100 nm". Under the above definitions, a nano-objects requires only one of its characteristic dimensions in the size range 1 to 100 nm to be classified as a nanoparticle, even if its other dimensions are outside that range. NPs have an impressively long history. They either exist freely in nature or are artificial (Griffin *et al.*, 2018). Examples of NPs which exist naturally include organic compounds (such as viruses, bacteria, proteins, and polysaccharides) and inorganic compounds (such as natural dust, aluminosilicates, and iron oxyhydroxides), which are produced by volcanic eruptions, microbial processes, weathering, and wildfires (Griffin *et al.*, 2018; Purev, 2016). However, it remains unknown how long NPs have existed in nature. Evidence of one of the earliest use of NPs is in glazes for the ancient Chinese dynasty porcelain. Another instance is a Roman cup from the 4th century referred to asLycurgus Cup(developed from nano-sized colloidal gold particles) which surprisingly possessed unique optical characteristics such that the cup showed a different colour depending on the direction of light passing through it – red when illuminated from behind and green when illuminated from the front (Leon *et al.*, 2019). Today, NPs are synthesised from a variety of materials, the most popular being ceramics, metals, polymers, semiconductors, carbons and organics (Abe, 2018; Álvarez-Muñoz *et al.*, 2016).

Considering the structure and composition, NPs can be of single properties such as dielectric, metallic, semiconductor, magnetic or multifunctional, including more than one feature from a single property. Compared to macro-sized particles, NPs possess exceptional physical and chemical properties such as catalytic properties, luminescent properties, photoelectric properties, biocompatibility, magnetic response, antimicrobial and many others (Sajid, 2020). As a result, NPs are consequently being applied in many fields for different purposes like in medicine for medical treatment of some cancers, imaging probes of various tumours, biological labelling and drug delivery; domestic use such as clothes and cosmetics; industrial products like batteries (oxide fuel) for energy storage and solar energy, optical devices, catalytic, semiconductor materials; environmentally such as in the treatment of contaminated water, sensor technology, and green manufacturing (Hasan, 2014; Jiang *et al.*, 2018; Salman-Ali, 2020).

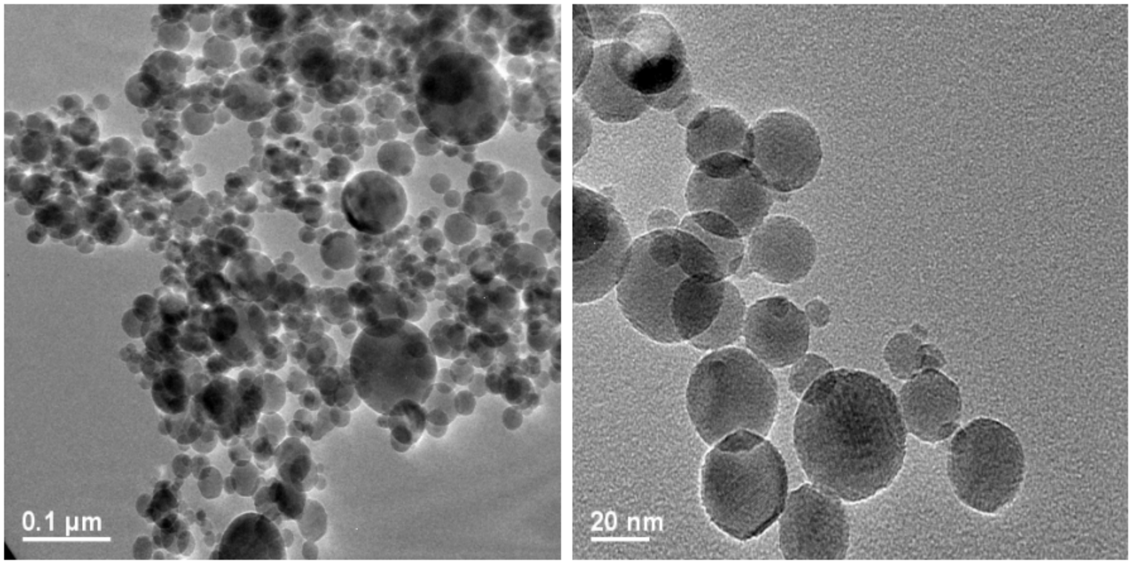

Figure 1. High-resolution TEM (HRTEM) images of plasma-synthesised alumina nanoparticles (Akbari *et al.*, 2011)

2.3 Classification of Nanomaterials

There are several approaches for classifying nanomaterials, such as their size, shape and material properties (Malhotra and Ali, 2018). Depending on their source or type of material, nanomaterials can be classified into carbon nanotubes, carbon fullerenes (buckyballs), nanolayers, nanocrystals and quantum dots (Álvarez-Muñoz *et al.*, 2016). Moreover, based on their shape or size of x, y, z dimensions, nanomaterials can be zero, one, two and three dimensional (0D, 1D, 2D or 3D) structural type (see figure 2) (Afolalu *et al.*, 2019; Afolalu *et al.*, 2021; Saleh, 2016), as discussed in the subsequent subsections.

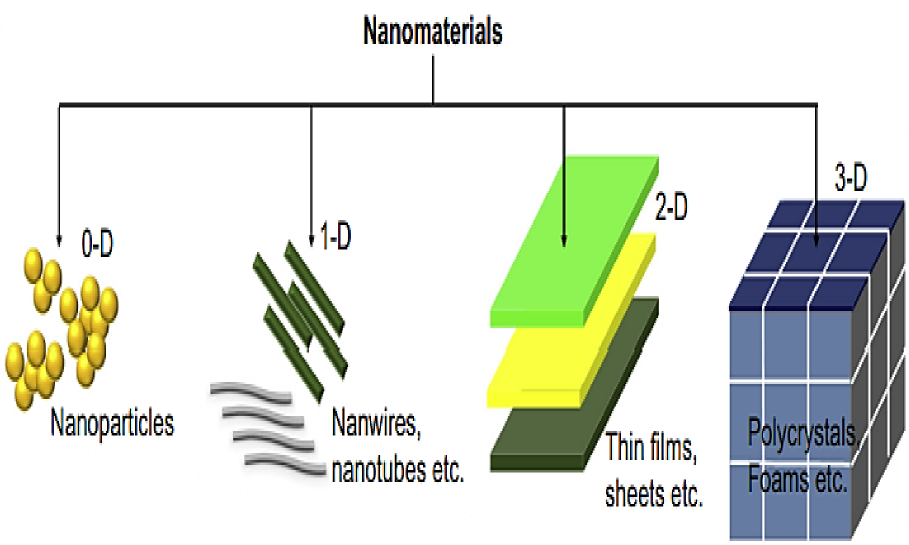

Figure 2. Schematic representation of nanomaterials (Malhotra and Ali, 2018)

2.3.1 Zero-Dimensional (0d) Nanomaterials
In 0D nanomaterials, the three dimensions are less than 100 nm and appear as dots (Salman-Ali, 2020). Most commonly synthesised 0D nanomaterials are quantum dots and nanospheres with diameters of 1 to 50 nm (Malhotra and Ali, 2018). However, these nanomaterials are challenging to create due to the fact that they easilycluster in solution and powder form resulting from the strong Van der Waals attraction that exists between them. Therefore, it is necessary to ensure a protection treatment after production or during their synthesis (Kebede and Imae, 2019).

2.3.2 One-Dimensional (1D) Nanomaterials
One-dimensional nanomaterials are shaped like filaments. These nanomaterials have particles in the macroscale (outside the nanoscale) range such that these materials have one dimension in the nanoscale range, and the other two dimensions can be outside the nanoscale (Malhotra and Ali, 2018). This class of nanomaterials includes nanotubes, nanorods, nanofibers, and nanowires (Salman-Ali, 2020).

2.3.3 Two-Dimensional (2D) Nanomaterials
2D nanomaterials have a minimal thickness but extend in a two-dimensional plane (expand in both x and y directions) (Tiwari *et al.*, 2012). This subset of nanomaterials exhibits plate-like shapes such as nanodisks, nanowalls, nanoplates, nanosheets, branched structures and junctions (continuous islands) (Salman-Ali, 2020).

2.3.4 Three-Dimension (3D) Nanomaterials
3D nanomaterials are particles in which all dimensions are in the macroscale(Malhotra and Ali, 2018). This class include bulk powders, dispersions of NPs, bundles of nanotubes, nanolayers and nanowires (Álvarez-Muñoz *et al.*, 2016).

2.4 Approaches in the Synthesis of Nanoparticles
Synthesis of NPs refers to the procedure of creating NPs. There are two main approaches to synthesising NPs: the breakdown or top-down approach and the build-up or bottom-up approach (Salman-Ali, 2020; Yadav, 2018), as shown in Figure 3.

2.4.1 Breakdown or Top-down Approach
The Breakdown approach has been in use for many years: since the early stages of nanotechnological research, it is more applicable for commercial purposes (Salman-Ali, 2020). This approach involves the cleavage of bulk materials into nano-sized particles by applying an external force such as mechanical milling, sputtering, laser ablation and nanolithography, to the material and later stabilising the particles to the required size (Nasrollahzadeh, 2019; Kalpana and Devi-Rajeswari, 2017). The significant disadvantages of this approach are that it is time-consuming, expensive, and the production of NPs with imperfect surface structures considerably impacts their physical and surface properties, thus precluding their applications in many fields (Malhotra and Ali, 2018). This approach is subdivided into the wet and dry grinding methods(Chelgani *et al.*, 2019). Forthe dry grinding method, a mill (roller, tumbling, shearing, jet or shock shearing) is used to grind the bulk material via friction. However,to obtain particle sizes less than 3μm using this method, is a significant challenge, due to the simultaneous condensation and pulverisation of small particles (Horikoshi and Serpone, 2013). Conversely, the wet grinding of the material can be done using an agitating, a planetary or a vibratory ball mill. This method is fitting for averting the condensation of the formed NPs so as to obtain highly dispersed NPs (Chelgani *et al.*, 2019).

2.4.2 Build-up or Bottom-up Approach
The bottom-up approach builds materials from the bottom: atom-by-atom, molecule-by-molecule into NPs, and is commonly used for the chemical and biological synthesis of NPs(Nasrollahzadeh, 2019). The principle behind this approach is based on self-assembly (molecular recognition) (Malhotra and Ali, 2018). Molecular self-assembly can be defined as the automatic arrangement of molecules into stable structures under close thermodynamic equilibrium conditions (Jassal, 2019). For instance, NPs can be nucleated and grown from ultrafine molecular distributions in liquid or vapour phases (Salman-Ali, 2020). More often, scientists use the bottom-up approach because it canproduce NPs with homogeneous chemical composition, uniform shape and size(Malhotra and Ali, 2018). Sol-gel, chemical vapour deposition, and pyrolysis are the most used bottom-up methods for NPproduction (Ealias and Saravanakumar, 2017). Figure 3 shows the Top-down and bottom-up approach for nanoparticle synthesis.

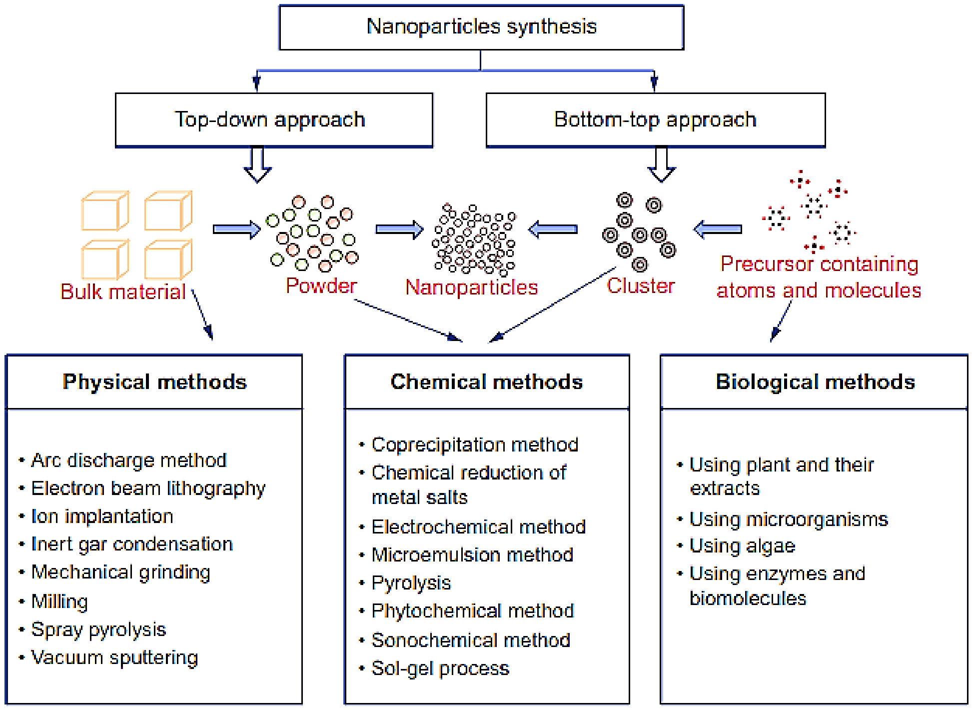

Figure 3. Top-down and bottom-up approach for nanoparticle synthesis (Devatha and Thalla, 2018)

2.5 Synthesis of Nanoparticles

Many different methods have been developed to synthesize and fabricate NPs with controlled size, morphology, dimensionality and structure (Rane *et al.*, 2018). The synthesis methods of NPs are broadly grouped into chemical, physical and biological methods (Roy *et al.*, 2018).Physical synthesis methods provide an environmentally friendly route in NP construction. This method can be divided into three subgroups: solid, liquid and gas phases (Karatutlu *et al.*, 2018).Chemical synthesis methods can be divided into two subcategories, namely liquid and gas phases. Even in the same initial phase, the critical difference between physical and chemical processing is whether chemical reactions are involved in NPs synthesis (Karatutlu *et al.*, 2018). The primary advantage of chemical methods over physical methods is the versatility in designing and synthesising novel materials that can be refined into finished products. The secondary advantage is good chemical homogeneity, as chemical processes offer to mix at the molecular (Tiwari *et al.*, 2012). However, a general limitation associated with chemical processes is the involvement of toxic reagents and solvents during NPs synthesis (Chatterjee *et al.*, 2020). Another limitation is the introduction of by-products which require subsequent purification steps after synthesis. Such purification steps usually are time-consuming (Tiwari *et al.*, 2012).The biosynthesis of NPs is regarded as green, economical and environmentally friendly alternatives to existing physical and chemical methods (Hasan, 2014). This method takes advantage of naturally occurring substances such as plants themselves or their active compounds (phenol, ascorbic and citric acid) (Augustine and Hasan, 2020), microorganisms (bacteria, fungi and yeast)and organic polymers (carbohydrates, fats and proteins) (Singh *et al.*, 2020) along with the precursors to produce NPs instead of conventional chemicals for bioreduction and capping or stabilising purposes (Saleh, 2016). For instance, there have been reports on the production of silver NPs from plant extracts such as aloe vera, papaya, cinnamon zeylanicum and lemon (Augustine and Hasan, 2020). On the other hand, in microorganism synthesis, The main advantages of biosynthesised NPs are nontoxic and biodegradable and allow the production of very small NPs (5 to 10 nm) (Küünal *et al.*, 2018).

2.6 Physicochemical Properties of Nanoparticles

The physicochemical properties of NPs are many; this makes them distinct and suitable for a wide range of applications (Table 1). These properties can be intrinsic, magnetic, optical and electrical, or extrinsic, such as surface characteristics and aggregation state (Rose, 2012). Other known properties of NPs include chemical composition, mechanical strength, reactivity and physiochemical stability (Mohamad, 2018).

Table 1. Properties of Nanoparticles.

S/N	Property Type	Characteristics	Reference(s)
1	Electronic	Specific NPs, such as the carbon nanotubes (CNTs), possess huge electrical conductivity but with little resistance and are therefore weak in the transmission of electromagnetic energy in their metallic state. Also, the electrical properties of metal NPs are to a large extent determined by Coulomb charge energy. This phenomenon can, in principle, be understood in terms of single-electron tunneling (SET) theory	(Salman-Ali, 2020) (Shi, 2015).
2	Optical	NPs posseses photoluminescent property that results in a displacement in the optical absorption spectra towards decreasing wavelength as the particle size reduces.	(Jamaludin *et al.*, 2019)
3	Magnetic	Preliminary investigations reveal that NPs exhibit profound magnetic properties at sizes between 10 to 20 nm (below the critical value) compared to macroscopic materials. Blocking temperature, Saturation magnetization, coercivity and Neel and Brownian relaxation time, are critical magnetic NPs parameters which can be easily manipulated to get the desired magnetic properties.	(Caizer, 2015) (Caizer, 2015; Kolhatkar *et al.*, 2013).
4	Thermal	A few of the unique properties peculiar to NPs are thermal conductivity, specific heat and thermoelectric power. CNTs have an elevated thermal conductivity, close to a factor of 2, greater than that of a diamond, meaning that they are also great heat conductors. Metal NPs and nanofluids (nanometric particles suspended in fluids) exhibit enhanced thermal conductivity than fluids in solid form. Nanofluids are required to show superior thermal conductivities relative to fluids which contains microscopic-sized particles and the conventional heat transfer fluids.	(Tao, *et al*., 2015) (Khan *et al.*, 2019) (Khan *et al.*, 2019)
5	Vibrational	There exists a continuous vibration of the atoms in NPs in a to and fro movement. Each nanoparticle possesses a unique set of vibratory motions called normal mode vibrations, which is determined by the particles' symmetry. CNTs have two standard modes of vibration. One mode is involved in the "in and out" oscillation of the tube's diameter, while the second mode crushes the tube, such that it pushes it down in one direction to extend vertically, essentially oscillating between an ellipse and a sphere	(Lungu *et al.*, 2015; (Krumrey, 2019). (Yoha *et al.*, 2020)

3. Conclusion

This study has established the importance and value that the use of nanotechnology offers in the 21st century. It has also highlighted the physicochemical properties, approaches to synthesis and classifications of nanoparticles. The future is promising if the many opportunities that nanotechnology offers are maximized.

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