Nano and bio-composites and their applications: A review

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Abstract. Recent developments in the materials science field have highlighted the need for further composite materials study, especially with regard to bio and nano-composites, as their abilities to meet modern requirements with regard to facilitating technological advancement is far greater than those of monolithic materials. There are several advantages to nano and bio-composites as compared to conventional materials, including properties such as fatigue resistance, impact resistance, stiffness, corrosion resistance, biodegradability, thermal conductivity, low relative density, environmentally friendly waste stages, and high specific strength. Recent years have seen the discovery of several new high-performing composite materials, and improvements in the fields of aviation, automobile, adhesion, building, and electronic engineering also support the adoption of more general utilisation of nano and bio-composites in a much wider range of applications than those for which they were originally designed. This paper thus highlights and reviews information on bio- and nano-composite materials to determine current trends in how these materials are used in the various fields of engineering in numerous applications, and to examine the role of nanotechnology in the enhancement of composite properties.

Keywords: Composite materials, nano-composite, applications, bio-nano-composite, bio-composite.

1. Introduction

Pure materials are often insufficient to meet the needs of modern technological requirements, while the use of two or more materials in phased combinations to form composites could theoretically meet these more rigorous requirements, as shown in the various applications of aluminium, steel, and their corresponding alloys. Composite materials are structured in such a way as to allow two or more than two material phases to be insolubly mixed at the molecular level. One component is identified as the matrix, which functions as the continuous phase, whereas the other material or materials are identified as the filler, reinforcing the composite [1-3]. The reinforcing phase may utilise either inorganic or organic filler materials. Inorganic fillers used in this way include a wide range of synthesised materials and minerals, while organic fillers (bio-fillers) are extracted from or produced by animals or plants. Composites exhibit numerous advantages over monolithic materials of conventional derivation, including several electrical and mechanical property improvements such as increased strength and stiffness, (dynamic crack propagation under cyclic loading)[4], resistance to impact, resistance to corrosion, electrical conductivity, and thermal conductivity. Nevertheless, composite materials have
their own limitations and drawbacks, and one major challenge is the cost of composite fabrication. The cost of some graphite-epoxy composites may be as high as 10 to 15 times the cost of a metal used for similar purposes [5]. However, in recent years, many improvements have been reported in manufacturing and processing techniques, which may significantly reduce such costs in the near future [6]. Composite structure modelling and analysis is also usually more difficult than that of metal structures, as metals are typically isotropic, while most composites are anisotropic, and their properties are not equal in all directions. Multiple parameters are thus required to be known in advance to predict even basic behaviours, such as the Poisson’s ratio and elastic modulus in each direction.

Recent developments in nano and bio-composite materials have led to the production of advanced composites to be utilised in aerospace engineering, high-tech instrumentation, aviation, and mechanical, buildings, packaging, and medical systems as well as electrical applications. Figure 1 presents the global distribution of composite materials ($ mil) by market segment in 2019 [7]. Several researchers have also recently shown that such composites perform well in reinforcement roles, offering additional efficiency in complex engineering conditions. Nano-composites have also been used in several new applications in various fields, such as battery cathodes, non-linear optics, ionicics, mechanically reinforced lightweight components, nanowires, sensors, and similar precision systems. A review of recent work by previous researchers on the application of nano and bio-composites for the development of advanced composite technology is thus required.

Viable property improvement strategies for the optimisation of nano-composite fabrication are currently in high demand; generally, utilising bio-composites instead of artificial materials is recommended, due to the increased cost-effectiveness and environmental friendliness of bio-composites. This has increased the need for the development of nano and bio-composite materials with advanced properties to meet the widely varying requirements of various applications. The motivation behind the current work is to increase the use of greener and biodegradable materials, and this review paper thus addresses advanced applications of nano, bio and bio-nano-composite materials in various engineering fields, with special attention to the future trends of this technology.

Figure 1. Composite material distribution ($ mil) by market segment in 2019 [7]
2. Information Analysis

2.1 Nano-composite materials

Nano-composite materials are those structural materials wherein at least one of the phases has a dimension of less than 100 nm. Use of nanoparticles instead of micro-particles in many applications results in greater changes in physical properties [8, 9], as nanoparticles have a large surface area for a given volume [10]. As particle surface and properties govern all chemical and physical interactions, a nanostructured material may possess notable improvements in properties from micro-structured materials of otherwise similar composition [8]. In general, for plate fillers, fibres, and particles, the surface area is inversely proportional to the thickness and diameter. Hence, smaller thickness and/or diameter results in higher surface area per unit volume [11]. Figure 2 presents some common shapes of filler particle and their surface area-to-volume ratios: for nanofillers in the form of fibre, layers, and tubes, the surface area-to-volume ratio is controlled by the first part if the equation, while the second part of the equation \( \frac{2}{L} \) and \( \frac{4}{L} \) is very small (negligible). Thus, as shown in Figure 2, particle diameter reduction from micro- to nano-scale will increase the surface area ratio to the volume by three magnitude orders. When the filler possesses a higher aspect ratio (30 to 1,000) and a plate-like structure, such as in organic silicate, this is classified as a layer of nanomaterial. Generally, nanomaterials act as reinforcement due to their high aspect ratios, which has allowed nanomaterial fillers to be utilised for the formation of various composite materials [12, 13].

![Figure 2. Common filler particle shapes and their surface area to volume ratios [12]](image)

Notable enhancement in the properties of nano-composite materials depends not only on their surface area, but also on their morphology, interfacial characteristics [14], and the degree of mixing between phases. The influence of these respective parameters is based on the properties of composites and the nature of the chemical compounds comprising the filler and matrix [15]. Certain nanocomposites may possess properties heavily influenced by quantum effects, while others exhibit more interfacial interaction effects associated with their nano-dimensional structures [16]. When the fundamental physics and length scale (diameter of nanoparticles, diameter and length of nanofibres and nanotubes, and thickness of nanoplates) of the particle morphology associated with a property coincide, property improvement can be significant [17]. Such effects were reported as early as the 1990s by Kojima et al. [18], working at the Toyota Central Research Laboratory in Japan. In their studies, small amounts (1.8, 3.6, and 6.6 wt.%) of nano-filler (clay) loading produced a significant improvement in the mechanical and thermal properties of nylon-6 nanocomposite. This improvement in properties was attributed to the uniform dispersal of clay in the matrix bonding the nylon-6 and clay filler to each other by means of ionic bonds. Over the past three decades, many other studies [19-21] have produced high-performance nano-composites by utilising the effect of length scales. Recently, Bari and Mishra [22] reported on the
effect of length scale by incorporating calcium sulphate (CaSO$_4$) nano-rods (1, 2, 5, and 7 wt.%) into chitosan polymer using a solution blending process; they found that the mechanical properties were increased by ~20% with 5 wt.% CaSO$_4$ nano-rods, which they attributed to the high aspect ratio of CaSO$_4$ nano-rods and the resulting enlarged surface area.

2.2. Bio-composite materials

Composite materials consisting one or more phases extracted from biological sources are known as bio-composites; these often include plants fibres such as those from waste paper or recycled wood, flax, hemp, and cotton, as well as waste from food crops [15]. Lately, researchers have become even more interested in bio-composites that can be strengthened with biopolymers or natural fibres [23]. These exhibit various advantages, such as renewability; low density, which may be as low as 40%; biodegradability; cost-effectiveness; and high specific strength (the strength/density for Flax is 18.5% higher than for E-glass) [16]. Figure 3 illustrates a classification of completely or partially biodegradable composites.

![Figure 3. Bio-composite classification [24].](image)

Recently, there has also been increasing interest in developing bio-based and biodegradable polymers to use as an alternative to fossil-based polymers. Bio-based polymers combined with natural fibres are key innovations in the trend towards more sustainable lifestyles and improvements in green technology, as such materials are truly green in every way and, at the end of life, can be easily composted or disposed of without harming the environment [25]. Bio-composites and green composites as terms thus refer to the same material class. However, some mechanical (brittleness) and barrier properties of biopolymers are poor compared to those of conventional plastics [17]. In addition, natural fibre has high moisture absorption, incompatibility with certain polymeric matrices, and poor wettability. The hydrophilic property of natural fibres which cause this moisture absorption also adversely affect the mechanical properties such as flexural modulus, fracture toughness, and flexural strength [26]. Nanotechnology development in the biopolymer field has greatly improved the potential functionality of biopolymers. A matrix of biopolymer which incorporates a discontinuous nanofiller with a particle diameter less than 100 nm is known as a bio-nano-composite [27]. Figure 4 shows the differences between micro composite and nano-composite morphology. A nano-sized filler has an increased contact
surface area with the matrix of the biopolymer, encouraging strong interaction in the filler-matrix system compared to that in a micro-composite [27]. The mechanical properties may also be enhanced due to high rigidity of nano-sized fillers where acceptable affinity between the biopolymer matrix and nano-sized fillers is achieved [17]. As mentioned by Huang et al. [28], the addition of nano-clay in a ratio of 5 wt.% to corn starch/montmorillonites (MMT) offers a significant increase in tensile strength, from 4.5±0.3 to 21±0.5 MPa (450%), and tensile strain, from 109±1.4% to 134.5±0.7% (20%). These increases in mechanical properties are related to the aspect ratio and high rigidity of nano-clay and the good dispersion and affinity between the biopolymer matrix and nano-clay.

![Figure 4](image-url)  
**Figure 4.** Morphology of a micro-composite (a) and nano-composites (b) and (c) [19]

Materials with the potential to form bio-composites, such as cellulose, starch, soy-based resins, lignin based epoxy, and polylactide, may thus contribute to fossil-based resource reduction. In addition, cotton, jute, flax, hemp, sisal, kenaf, corn, and soy are widely utilised as strengthening agents in biofibres to replace synthetic fibres [29]. Figure 5 illustrates some common uses of bio-composites and highlights some specific applications.
2.3 Bio-nano-composite materials

Bio-nano-composites refers to materials that utilise natural species (mainly biopolymers such as cellulose, agar, and chitosan) as a matrix or continuous phase with the inclusion of organic (clay) or inorganic (metal, metal oxide) materials at the nanometre scale (< 100 nm) to enhance certain properties in the resulting composite materials [27, 31]. Due to the combination of natural polymers and solid content in these materials, they differ from nano-materials in terms of application, biodegradability, biocompatibility, and functionality [32–36]. Bio-nano composites represent a remarkable type of nanostructured hybrid materials with several new structural and functional properties that are applicable to a wide range of technologies [37], including applications in the medical, food, industrial, ecological, and agricultural sectors. Many researchers have devoted their work to the development of bio-nano-composites with improved mechanical, thermal, and functional properties based on varying nanoparticle fillers or matrix. Biopolymer-based technologies are commonly known as green technologies based on their biocompatibility and biodegradability, and these are particularly applicable to agricultural, pharmaceutical, and food packing technologies [38, 39]. Biosensor applications that include bio-nano-composite materials have also shows the capability to respond to changes in the environment, including food product contamination and changes to levels of oxygen, humidity, degradation, and temperature that may promote food safety.

Related to this, the antimicrobial function of some nanocomposite materials or nanoparticles has long been recognised and utilised in various industries such as the packing sector, with antimicrobial packing films or antimicrobial carriers being a common application. Nanocomposite antimicrobial systems are particularly effective due to high surface-to-volume ratio and improved surface reactivity of the nanosized antimicrobial agents, which enable them to inactivate microorganisms more effectively than their macro-or micro scale counterparts [40]. In food packaging applications, the most commonly used bio-nano-composite materials are clay-based [41]. Such applications tend to have several specific requirements in common: biodegradability, antimicrobial activity, biocompatibility, good mechanical properties, high absorbency, cost-effectiveness, eco-friendliness, and renewability [33, 42, 43].

Figure 5. Applications of bio-composites [30].
3- Applications
Composite materials can be tailored to promote various properties based on the careful selection of components, proportions, distributions, morphologies, and crystallographic textures, as well as the composition and structure of the interface between components. By amending these properties, composite materials can be tailored to meet the needs of various applications, and nano and bio-composite materials also provide advanced properties applicable in various fields, such as industrial design (gas tanks, bumpers, exterior and interior panels), construction works (building sector and structural panels), aerospace and aviation (panels of flame retardant and components of high performance), textiles, food packaging, medical applications, photonic crystal creation, and electronic adhesion, and coating [44]. Figure 6 shows several common reinforcement bio-materials and their corresponding applications.

3.1 Automotive
A growing awareness of the value of nanocomposites has helped investors to identify that these materials herald a new era in material development, with polymer composites transforming multiple industries in recent years. Nanoscience has played a significant role in the enhancement and improvement of the properties of existing materials, and polymer composites have been a mainstay in the automobile industry for over 25 years due to their compatible performance behaviour with its numerous desirable properties such as thermal stability, strength, and high stiffness. The implementation of nanotechnology has made such polymer composites even more attractive, and just as polymer composites changed the face of the industry twenty-five years ago, polymer nano-composites are now leading the way into a new era of material development [45]. Due to their specifications, polymeric nano-composites have several distinctive properties, such as enhanced mechanical properties, heat resistance, impact resistance, and physical properties. Several researchers have thus been working on using the unique properties of nano-composites in conjunction with recyclable polymers to produce lightweight biodegradable, recyclable polymer nano-composites, although this has been shown to be technologically

![Figure 6. Common reinforcement bio-materials and their applications](image-url)
challenging, as such materials could be useful in car bodies and other systems requiring vibration damping. Buchholz [46] utilised polymer nano-composites as “step assists” in the General Motors Safari and Astro vans; these composites have high scratch resistance and surface hardness, improved strength, reduced weight and a rust proof nature, thus offering reduced fuel consumption and increased life-span for these vehicles. Liang et al. [47] analysed the effects of using three types of graphene nano-plate (GNPs) as nano-fillers at ratios of 0.1, 0.2, 0.3, 0.4, and 0.5 by wt.% of polymer matrix (polypropylene) based on high speed compounding, melting, and extrusion of the composite. Their study showed that the value of tensile yield strength was enhanced slightly, by 10%, compared to that of the raw material (31 MPa), while the tensile fracture was increased by about 20% from the 26 MPa for the raw material. The most significant increase was found in the Young’s modulus, which showed a 108% increase when compared with that of the raw matrix (1.25 GPa). This reinforcement could be due to the relatively high interfacial adhesion and large interfacial areas between the GNPs and polypropylene, and it is certainly a noteworthy effort towards the development of polypropylene composites using nano-filler to overcome disadvantages such as low stiffness and poor impact toughness.

The production of nano-composite materials with enhanced mechanical properties makes them more suitable for applications in automobile structures, and bio-composite applications in the construction sectors and automotive industry are already quite extensive [29]. Figure 7 shows the use of natural fibres in composites in the European automotive industry in 2012.

![Natural fiber use for composites in the European automotive industry in 2012](image)

**Figure 7.** Natural fibre use for composites in the European automotive industry in 2012 [48].

Suddell and Evans [49] used cotton fibres as a bio-composite filler in automotive, adding the material to the polyester matrix used in the car body for East Germany’s Trabants. Another application of bio-composites in the automotive industry was the use flax fibres instead of fibreglass in car disk brakes by Daimler–Benz in 1991 [49]. Kenaf fibres are one of the most likely choices to replace fibreglass in the production of composites in Malaysia; as Kenaf is widely cultivated in Malaysia, the cost of production of these types of bio-composites can be reduced. One application that has successfully been researched during the last few years is the material’s use in the interiors of cars [50]. In this process, Kenaf fibres are first processed using a carding machine prior before being shaped into a pressed mat; this is then impregnated with polylactic acid resin, then hot pressed in a mould to create the final product. Test results reveal that the mechanical properties of this material satisfy the requirements of automotive manufacturers, and the volatile organic compound (VOC) emissions are very low.

Alongside these applications, bio-composite materials have been used to make the blades of a small turbines [51, 52]. In such cases, composites made of flax fibres reinforced in a polyester matrix were used, and the density of such blades (1.29 to 1.5 g/cm³) shown to be less than the density of blades
conventionally made of E-glass fibres (2.66 g/cm³). It has also been proven that this material can withstand the required ultimate tensile strength and operational loads of turbine use. Although the inclusion of natural fibres makes the composite more flexible, such that the flax blade has a tip deflection higher than that of the E-glass blade by 40%, several further improvements have been reported with regard to the design of such blades that increase rigidity [51]. Bakri [53] made other bio-composite materials for use in small turbines, however, with composites made from coir fibres with coconut husks as a reinforcing epoxy matrix. The material showed similar mechanical properties to wood, a more conventional material for a wind turbine, though this composite was inferior to those made from fibreglass.

3.2 Rubber and Tire Industry

The incorporation of bio and nano-composites into tire components generally results in higher overall performance, especially in terms of increased fuel efficiency via reduced energy absorption and weight from rolling resistance, and more favourable economics derived from reduced complexity of construction, easier processing, and the substitution of less expensive polymers. These overall motivations translate into specific development goals with regard to

- Improvement in performance of tire tread via reduced heat build-up (rolling resistance), better wear, and improved traction.
- The enhancement of air retention.
- Colour/transparency.
- The reduction of heat build-up leading to a decrease in tyre failure.
- The reduction of halogenated butyl, resulting in easier disposal and/or recyclability [54].

A large proportion of the published literature thus describes the role of bio and nanomaterials in enhancing rubber performance. Bamboo filler is often used to improve the mechanical and physical properties of tires; as a natural fibre, bamboo filler used in elastomer composites can enhance abrasion resistance [55]. Kang et al. [56] developed a graphene (GE)/natural rubber (NR) nanocomposite with high levels of dynamic properties using direct mechanical mixing. This nanocomposite was utilised in vibration isolation systems and pneumatic tire applications with several different fillers such as graphite, carbon black, and graphene (GE), with multiple improvements in various mechanical (17% increase in tensile strength for GE/NR composites) and dynamic properties over conventional materials. Another investigation on the effect of nanomaterials in the tire manufacturing field was conducted by Qiao et al. [57], who analysed the interfacial interactions between silica and group-functionalized styrene-butadiene rubbers (G-ESBRs) and the static and dynamic mechanical properties of epoxy (G-ESBRs)/silica without the addition of further coupling agents. Excellent improvements to the mechanical properties (55% increase in tensile strength compared with nano-composite without epoxy group) were reported when glycidyl methacrylate (GMA) at 4.8 wt.% was used. This improvement was attributed to the ring-opening reaction between the epoxy group of G-ESBR and the hydroxyl on the surfaces of the silica (Figure 8), leading to the formation of covalent bonding. The new material showed higher performance and stronger interfacial interactions than conventional materials, as well as excellent performance with regard to the dispersion of silica.
Figure 8. Silica/G-ESBR nanocomposite with covalent bonding interfaces without coupling agents [57]

Figure 9 shows the TEM images for silica/styrene 40% (S40)-GMA 0% (G0) and silica/S40-G5 nanocomposites. The black spots in these images represent silica particles, showing that there are multiple silica aggregates with poor dispersion in S40-G0 due to low compatibility (Figures 9 (a-c)). Figures 9 (b-d) illustrate the improvement of the dispersion of silica, with relatively uniform outcomes, in S40-G5, which has fewer aggregates due to the incorporation of the epoxy group. This enhancement in the dispersion is attributable to the strong covalent bonding interfaces produced by the ring-opening reactions between the silica and G-ESBR, which lead to improvements in the interfacial interactions between the G-ESBR and silica.

Figure 9. TEM images of (a and c) silica/S40-G0 and (b and d) silica/S40-G5 [57]
3.3 Aircraft

Nano-fillers and organoclay have been introduced to hydrogenated nitrile rubber (HNBR) as a result of rapid advancements in nanotechnology in the polymer industry. HNBR are elastomers that act as filler systems for high-performance nano-composites that satisfy demand from the aerospace industry for use in extreme operating conditions, offering an extended life-span of service based on enhanced air/water/oil resistance and thermal stability at extremely high temperatures. When HNBR/clay nano-composites are exposed to high temperatures of around 700 °C, the layers of organoclay provide effective barriers, in the form of tortuous paths, to heat, oxygen, water and oil; these paths slow down the mass rate loss during the thermal decomposition of HNBR/clay nano-composites [58].

Lalli and Claus [59] examined metal rubber and reported that the nano-composite was constructed through a self-assembly process triggered by metal and elastomeric polyelectrolytes. This type of processing permits control over various mechanical and electrical properties and requires only small parts per million (ppm) quantities of metal to achieve percolation. The use of nanostructured precursors also produces electrically conductive and transparent nano-composites. Currently, elastomers based on metal rubber are also being developed as sensors for the detection of large strain fatigue and impact for aerospace applications. Lagashetty and Venkataraman [60] studied the resonance performance of polymer nano-composites utilising ferrite as a filler. They found that this material showed good potential for use in aerospace applications, such as microwave absorbers, sensors, and similar applications due to its magnetism, mouldability, and cost effectiveness.

Other research examined electromagnetic absorbers based on nano-composites for applications in aircraft and wireless communication [61]. However, there are several drawbacks to currently available electromagnetic absorption materials such as their limitation to fixed frequency bands, high weight, and reduced durability. Nonetheless, electromagnetic absorbers can be made from reinforced polymer composites with magnetic nanoparticles (NPs) to form smart structures, with composites of carbon nanotubes exploited by electric, magnetic, or thermal electric current energy to change the shape of parts or to produce force from a power source, usually an amplifier. Such structures are “aware” of their states and thus capable of responding to changes in operating environment or other exciters intelligently. Consequently, carbon nanotubes can be usefully used as part of aircraft smart structures [62].

Policandriotes and Filip [63] used single-walled carbon nanotubes for this purpose, with a composite of Si, SiC, and single-walled carbon nanotubes (SWCNT) used as nano-additives in commercial C-C composites using ultrasonic mixing in an attempt to fill the open porosity in an aircraft’s breaking disk. That study reported that Si and SiC showed distinctive effects on the friction performance in the hot taxi after landing, increasing the effective friction coefficient value by 60% at ~0.6 wt.% Si and by 25% at 0.21 wt.% SiC with respect to the raw matrix, with very small percentages (3.35 to 3.71%) of weight loss. Another investigation by Lapcik et al. [64] studied the effects of nano-particle shape on the properties of polyolefin composite parts made for the aerospace and automotive industries. Several nano-particle shapes were used that adopted calcium carbonate (hollow sphere shape), flash calcined kaolin (agglomerate shape), dolomite (lamellar shape), and calcined kaolin (lamellar shape) as nanofillers in polyolefin composite. The study found that particle shapes significantly influence the mechanical and acoustic properties of the powder bed due to variance in the packing density, and that such properties make some of them more suitable for aerospace applications.

3.4 Adhesives

There have been several attempts to overcome the challenges involved in adhesive bonding that can negatively influence mechanical properties, with several suggestions and techniques to improve the joints used in aircraft structures emerging. Many researchers have confirmed that the introduction of fillers can mitigate shear strain in the transfer of longitudinal loads; however, although these researchers have improved the adhesive materials properties utilised in aircraft, nano-composite technology has shown even more rapid development in general engineering properties [65]. Mechanical properties in general and shear strength in particular have thus been enhanced by introducing CNT and MWCNT as reinforcement to adhesive materials. In their investigation, Gkikas and Sioulas [66] found that the
incorporation of a small fraction by weight (0.5 and 1 wt.%) of multiwall carbon nanotubes in a polymer adhesive film provided additional active enhancements, creating an effective corrosive barrier that prevented electrolyte penetration to the surface of aluminium and improved the adhesion between the film and the alloy substrate by around 50% compared to the raw matrix, as well as producing a hybrid system with galvanically compatible constituents. A primer layer of epoxy nano-composites can thus be used to improve the anticorrosion properties of aircraft coating.

Despite these considerable enhancements, aircraft manufacturers still require more confidence for the widespread use of new bonded repair technologies to become common in the aircraft industry [66].

Another adhesive material development was thus reported by Akpinar et al. [67], who examined the effects of adding nano-fillers (Fullerene C60, Graphene-COOH, and CNT) in ratios of 0.25, 0.5, 1, 2, and 3 by wt.% to three types of adhesive materials (DP460 toughened adhesive type, DP270 rigid adhesive type, and DP125 flexible adhesive type) using AA2024-T3 aluminium alloy as the adherent. The failure loading of the joints (single-lap joints as used in automotive, aerospace, and space applications) of DP270 rigid adhesive type increased by around 276% at a ratio of 2 wt.% of Graphene-COOH and that of DP125 flexible adhesive type increased in a range of 40 to 65% at a ratio of 1 wt.% Fullerene C60, while the failure load of DP460 toughened adhesive type increased by 28% at a ratio of 1 wt.% Fullerene C60. These increases may be due to structural features of the adhesives and the types of resultant nanostructures. The joint failure load was, in any case, significantly influenced by the state of adhesive with respect to toughness, rigidity, or flexibility [68].

3.5 Electronics

Conductive nano-composites can conduct electric current due to the free electrons available in their structure. Polycarbonate is a common conductive thermoplastic polymer material, offering a cheap plastic with superior mechanical and optical specifications that has several new potential applications. The electrical conductivity of polycarbonate is poor compared with that of good conductors, however, and researchers at the University of Houston addressed this by adding carbon nanotubes to increase its conductivity, making it highly conductive. This technique allows relatively cheap plastic to be used to make optical discs suitable for electronic aircraft applications [65]. Modern nano-materials, such as nano-composites of quantum dot solar cells, also yield electricity in a more efficient manner, allowing solar farms to generate more electricity with current footprints, and these abilities could be applied in the context of several modern smart city projects alongside other material science advancements in sensor technology [69]. Bio-composite materials have also been used in the field of electronic applications: chemically modified soya bean oil and hollow keratin fibres have already been used as electronic materials, as these composites have low dielectric constants due to the presence of air in the hollow microcrystalline of fibres of keratin and triglyceride molecules [40].

3.6 Oil and Gas Pipelines

It is necessary to control and avoid corrosive damage in oil and gas pipelines, as the materials used are exposed to extreme operating conditions, which often push the design life of the materials beyond their original design life-span [65]. The main idea underlying the utilisation of nano-composites in mechanical systems is to enhance resistance to fracture failure and the occurrence of wear and tear on parts. Kessler and Goertzten [70] pointed out that the use nano-composites in pipelines is highly recommended, as further repair processes can be completed in a relatively short period of time, allowing the transmission of fluid in the piping system can remain undisrupted when minor repair works are in progress; in particular, overwraps can be utilised to repair rusted steel pipelines, while fibre-reinforced nano-composite pipelines can be utilised as full substitutes for steel pipelines with a good performance and cost balance. Mays [45] further highlighted that there are many advantages to the application of reinforced nano-composites in oil and gas pipelines, including good collapse pressure ratings, extraordinary burst, increased capacities in terms of load carrying, increased compressive and tensile strengths, and the ability to install many kilometres of continuous pipeline as a seamless whole [65]. Boroujeni et al. [71] found that CNTs grown on the surface of carbon fibre could enhance various
properties of in-plane and out-of-plane epoxy polymer composites such as off-axis-stiffness, which was enhanced by 16%, and ductility (35%), while the on-axis tensile strength was increased by (11%). Such improvement makes the material even more feasible for use in pipeline systems. The enhancement of the hybrid composite’s properties can be attributed to the surface growth of the CNTs. The hybrid composite with fine pattern growth CNTs demonstrated the highest strength and stiffness along the on-axis direction, suggesting that pattern growth also has a significant effect on the of-axis elastic modulus, as the coarse pattern growth CNTs showed no significant enhancement (Figure 10).

As reported by Saliba et al. [72], a pipeline coating was developed using fusion bonded-epoxy (FBE) along with nano-SiO2, chemically modified with (3-aminopropyl) tetraethoxysilane (3-APTES). This treatment resulted in a significant increment in hardness and modulus of elasticity of 17% as compared to the raw counterpart. Their study further showed that this enhancement in the mechanical properties of the composite could be attributed to the covalent bonding between the FBE and an organofunctional group from the surface, as shown in Figure 11.
SEM analysis revealed that the silica-nanoparticles were uniformly dispersed in the FBE epoxy powder which, after thermal treatment and the curing process, led to the formation of a homogenous nanocomposite coating (Figure 12) [72].

![SEM image of FBE- NanoSiO$_2$ -APTES coating with nanoparticles, heat dried at 400 °C.](image)

Figure 12. SEM image of FBE- NanoSiO$_2$ -APTES coating with nanoparticles, heat dried at 400 °C. [72]

3.7 Protection systems (corrosion resistance)

Protection against corrosion has been the subject of pronounced industrial and scientific interest in recent decades. The main source of effective and environmentally friendly substances for the prevention of corrosion is cerium salts, commonly used in aluminium alloys. Madhuri et al. [7] investigated pre-treatment of AA2024-T3 aluminium alloy with nano-structured sol-gel coatings doped with cerium ions, though many researchers have noted that the use of cerium oxide may prevent corrosion. One of the most widely used protection system evaluation techniques is salt fog testing, which generates the spontaneous deposition of the cerium oxide; this was developed to protect aluminium alloy (7075-T6) against corrosion for up to two weeks (336 hours) [73].

Lamaka et al. made compounds of Mercapto BenzoThiazole (MBT) and 8-HQ (8-hydroxyquinoline) as inhibitors of corrosion for AA2024-T3, noting that these inhibitors provide anti-corrosion protection for AA2024-T3 via the formation of a thin organic layer on the alloy surface. The protection is the consequence of the prevention of Al, Cu, and Mg dissolution from corrosion activated intermetallic regions [74]. Yasakau et al. [75] thus studied the addition of 8-HQ at different steps of the synthesis process to help develop an understanding of the effects of possible interactions of the components of the sol-gel system with the inhibitor. Zheludkevich et al. [76] then evaluated MBT in neutral chloride solutions for use as a corrosion inhibitor to protect AA2024-T3. These nanocomposites are normally synthesised hollow nano-composites loaded with different compounds that prevent corrosion inhibitors, and are thus used as storage for inhibitors in corrosion protective coatings or to create delivery systems for inhibitors (Figure 13). Encapsulation of corrosion inhibitors has been proven by means of FT-IR spectroscopy and heat treatments. TGA measurements also show that the inhibitors are measurable within the nano-containing. The behaviours of this complex system (nano-containers and inhibitors) were tested in a corrosive environment by means of potentiodynamic, electrochemical impedance spectroscopy and UV-vis spectroscopy, which showed excellent results.
Figure 13. Multiscale anti-corrosion protection system [44]

CNTs have also been used as a filler in the form of multi-walled carbon (MWCNTs) in protection materials [77]. The relevant study utilised MWCNTs at different loading concentrations to reinforce epoxy matrix and the composites produced showed improved mechanical properties and anti-corrosion properties. The researchers found that when milled steel was coated with a MWCNT/epoxy nano-composite with 0.75 by wt.% MWCNTs, the rate of corrosion was decreased by $2.5 \times 10^{-3}$ MPY, with the efficiency of protection increased by up to 99.99%. This outcome is generally regarded as one of the most outstanding achievements in the field, with multiple industrial applications.

3.8 Medical

A perfect biomaterial is biocompatible and non-toxic, with suitable physical and mechanical properties. Naturally derived bio-materials are thus eminently suitable for medical applications due to their biodegradability, biocompatibility, ability to adsorb bioactive molecules, and non-toxicity [78, 79]. Sharabi et al. [80] demonstrated the use of a unique bio-composite for medical applications; the bio-composite in question, used in engineered soft tissues, was made from micro-crimped long collagen fibre bundles extracted from a soft coral and embedded in an alginate hydrogel matrix. Karthick et al. [81] used a nano-powder derived from seashells at 2, 4, 6, 8, 12, 16, and 20 wt.% as a bio-composite filler for dental applications, mixed with Poly(Methyl methacrylate) (PMMA) to increase the latter’s mechanical properties. The results showed that the hardness increased by 49.52% and the wear resistance increased by ~ 33 at the ratio of 12 wt.% nano-seashell, offering important implications for dental applications. This improvement in mechanical properties was attributed to reduced porosity, uniform dispersion, and good interactions between filler and matrix. Kakar et al. [82] used luffa fibre as a bio-composite filler and polyactic acid as a matrix material for orthopaedic applications, as the resulting composites were suitable both for use in soft tissues and for the application of external bone plates. Rifat et al. [83] utilised a ZnO/poly(ethylene glycol)/ chitosan bio-nanocomposite for wound healing applications, while Maura et al. [84] prepared a bio-nanocomposite based on cashew gum and kaolinite to be used to protect drugs against acidic conditions in medical applications.

3.9 Military

In the recent years, bio and nanocomposite materials have been studied extensively for military applications due to their excellent mechanical properties, cost effectiveness, and light weight nature. Due to the potential foe exposure to extreme environmental conditions such as cyclic low and high temperatures, ultraviolet (UV) light exposure, high humidity, and alkaline environments, the performance of materials selected for such applications needs to be comprehensively elucidated. Marshahyo et al. [85] used ramie single fibre with reinforced epoxy to manufacture bulletproof panels for military applications. The plants from which ramie fibres are harvested are widely found in China, and this fibre is not only environmentally friendly, but also practically weightless. Several researchers
have reported on its use in safety helmets, with composites produced by reinforcing ramie fibres with starch-based biosizing materials. This type of composite is much lighter than conventional composites, and the processing method used for starch is simpler than that required for synthetic polymers. Ramie fibres are also used for other military applications: Marshahyo [86] made bulletproof panels by adding reinforcing fibres of ramie to an epoxy matrix; although the material was found to be only applicable for a limited standard of bulletproof panels, it was distinctly lower in cost and lighter than synthetic fibres.

Overall, the key challenges for the development of nanocomposite materials that exhibit improved properties, whether physical, optical, barrier, or other, compared to micro or macro composites are the dispersion and adhesiveness of nano-materials with the matrix material, as well as ensuring the results are capable of handling a wide range of applications. There are several avenues for the improvement of dispersion and interfacial properties in both developed materials and those currently in development. Tables 1 and 2 show the most common applications and recent developments for associated properties required for nano and bio-nano-composite materials, respectively.
| No. | Field          | Author & Ref.     | Composite Model | Contribution | Application                                  | Properties required                      |
|-----|---------------|-------------------|-----------------|--------------|----------------------------------------------|------------------------------------------|
|     |               |                   | Matrix          | Filler       | Properties                                    |                                          |
|     |               |                   |                 |              | Enhancement %                                |                                          |
| 1   | Adhesives     | Chaabouni and Boufi [87] | Polyvinyl acetate (PVA) | Cellulose Nanofibre | Shear strength 220% | General applications - Better interfacial bonding. - High anticorrosive. - Icephobic (minimal ice adhesion in aeronautical applications). - Thermal properties. - Fracture toughness. |
|     |               | Gikias et al. [66] | Polymer adhesive film | Multi-wall carbon-nanotubes (MWCNTs) | Adhesion efficiency 50% |                                          |
|     |               | Kwon et al. [88]   | Epoxy           | Multi-wall carbon-nanotubes (MWCNTs) | Pull strength 92% |                                          |
|     |               |                    |                 |              | Thermal conductivity 50% |                                          |
|     |               | Ghosh et al. [89]  | Epoxy           | Nano-titanium oxide (TiO$_2$) | Lap shear stress 106% |                                          |
|     |               | Pirayesh et al. [90] | Amine-cured epoxidized polysulfide polymer | Graphene nanocomposite (GO) | Hardness 16% |                                          |
|     |               |                    |                 |              | Tensile strength 25% |                                          |
|     |               |                    |                 |              | Elastic modulus 39% |                                          |
|     |               | Sung et al. [91]   | Nacre-like polymer | Nano-clay | Adhesion strength 64% |                                          |
|     |               | Xavier et al. [92] | Epoxy           | Nano-nickel oxide (NiO) | Tensile strength 36% |                                          |
|     |               |                    |                 |              | Hardness 72% |                                          |
|     |               |                    |                 |              | Adhesion strength 14% |                                          |
| 2   |               | Wang et al. [93]   | Aluminum (Al)   | Graphene nanosheets (GNSs) | Tensile strength 62% | Body structure - Brake systems - Accessories - Timing belt - Structural seat backs. |
|     |               | Cano et al. [78]   | Chitosan        | Nano-titanium oxide (TiO$_2$) | Young modulus 25% |                                          |
|     |               |                    |                 |              | Tensile strength 10% |                                          |
### Automobiles

| Material | Uses |
|----------|------|
| Kwon et al. [94] | Aluminum (Al) Carbon nanotube (CNT) | Tensile strength 299% | Body mouldings, Engine covers and catalytic converts, Batteries |
| Chatterjee et al. [95] | Poly(ε-caprolactone) (PCL) Single wall carbon nanotubes (SWCNTs) | Young’s modulus 562.7% |
| Imoisili et al. [96] | Epoxy Microwave treated plantain fibres/MWCNT | Hardness Impact strength Up to 20% Up to 27% |

### Aerodynamics

| Material | Uses |
|----------|------|
| Anmin et al. [58] | Hydrogenated nitrile rubber Nanoclay | Thermal stability Aging performance |
| LaBi et al. [59] | Rubber Metal | Mechanical Electrical |
| Durairaja et al. [61] | Lead-free solder (Sn/Ag/Cu) Nanonickel | Shear strength |
| Polcandriotes and Filip [63] | Commercial carbon (C)/carbon (C) Silica (Si) Silicon carbide (SiC) Single-Wall carbon nanotubes (SWCNTs) | Effective friction coefficient 60% with Si 25% with SiC 45% with SWCNTs |
| Hybrid epoxy + kenaf fibre | Tensile strength 24.9% with OPEFB | Ductile, High conductivity, lightweight, High strength to weight ratio, Reducing flammability, High-temperature resistance, High ballistic performance, Stabilized coefficient of friction for aircraft brake systems |
| Saba et al [97] | Oil palm empty fruit bunch nano fibre (OPEFB) | 20.7% with MMT | 29.3% with OMMT |
|---------------|-----------------------------------------------|----------------|----------------|
|               | Montmorillonite (MMT)                          |                |                |
|               | Organic modified Montmorillonite (OMMT)       |                |                |
|               | Elongation                                    | 37.5% with OPEFB | 16.2% with MMT | 9.5% with OMMT |
|               | Impact strength                               | 28.3% with OPEFB | 27.6% with MMT | 60.8% with OMMT |

| Cicek et al [98] | Polyvinyl alcohol (PVA) | Nano-graphene | Electrical Photoconductivity properties | - | Data storage | - |
|------------------|-------------------------|---------------|----------------------------------------|---|-------------|---|
| Khanra et al. [99] | Polyfluorene (PF) | Functionalization of diphenylalanine (FF) nanotube | Biodegradability | 80% | - | Communications | - |
| Li et al. [100]   | Benzo cyclobutene (BCB) | Boron nitride nanosheets (BN) | High-voltage capacity | - | - | Diodes | - |
|                  |                         |               | Energy storage capabilities | - | - | Computer chips | - |
|                  |                         |               | Low electrical conduction | - | 4.3×10⁻³% | lighting protection system | - |
|                  |                         |               | High operating temperature | - | - | Electrical sensing | - |
|                  |                         |               | - | - | Electromagnetic interface shielding | - |
|                  |                         |               | - | - | Electron emitting flat-panel displays, Electromechanical actuators | - |
|                  |                         |               | - | - | Light-emitting diodes; supercapacitors, Field-effect transistors, Sub-picosecond optical switches and optical limiters. | - |

| Saliba et al, [72] | Fusion bonded-epoxy (FBE) | Nano-SiO2 | Hardness | 17% | Pipeline manufacturing | - |
|                   |                         | Modulus | 17% | | Corroded repair materials | - |
|                   |                         |         | | | Anticorrosion | - |
|                   |                         |         | | | Light weight | - |
|                | Oil and Gas Pipelines | Tire Industries |
|----------------|-----------------------|-----------------|
| Amirdehi [101] | Polyaniline Nanosilica (SiO$_2$) Corrosion resistance - | Pipes inner and outer protective layer Inflammable Abrasion resistance Thermal conductivity High burst and collapse pressure rating capability |
| Zhang [102]    | Aramid fibre/epoxy Nanosilica (SiO$_2$) Tensile strength 7.6% Flexural strength 2.6% Compressive strength 106.8% | |
| Parpoor [103]  | Polyethylene Nanoclay+ nanocopper (Cu) Young's modulus 117% Tensile strength 13% Yield strength 21% Electrical conductivity - | |
| 6              | Chen et al. [104] Natural rubber (NR) Nano-SiO$_2$ Thermal aging resistance - The storage module - Energy of relaxation activation - | Tyre trade manufacturing Rubber goods manufacturing High abrasion resistance High thermal properties High modulus of elasticity High durability |
|                | Kang et al. [56] Natural rubber (NR) Nano-graphene Tensile strength 17% | |
|                | Qiao et al. [57] Group-functionalized styrene-butadiene rubbers G-ESBRs Nano-silica (SiO$_2$) Tensile strength 55% | |
Table 2. Literature list for bio-nano-composite applications and properties’ improvement

| No. | Field             | Author & Ref.                  | Composite                                                                 | Contribution                  | Application                                                                 | Properties required               |
|-----|-------------------|--------------------------------|---------------------------------------------------------------------------|------------------------------|----------------------------------------------------------------------------|-----------------------------------|
| 1   | Medical           | Yadollahi et al. [105]         | Chitosan                                                                  | Nanosilver                   | Antibacterial                                                             | Tissue engineering              |
|     |                   |                                |                                                                           |                              | Swelling                                                                  | Biodegradability                  |
|     |                   | Costa et al. [106]             | Polyvinyl alcohol (PVA)                                                   | Pineapple (Nano cellulose)   | Thermal                                                                   | Drug delivery systems            |
|     |                   |                                |                                                                           |                              |                                                                            | Antimicrobial activity            |
|     |                   | Boroujeni et al. [107]         | DCPA cement                                                               | MWCNTs                       | Compressive strength                                                    | Cement for orthopaedic applications |
|     |                   |                                |                                                                           |                              |                                                                            | Biocompatibility                  |
|     |                   | Sharma et al. [108]            | Polymer (chitosan, gelatine, and alginate)                                | Nano-hydroxyapatite (n HAp)  |                                                                            | Cost-effective                    |
|     |                   |                                |                                                                           |                              | Swelling                                                                  | Mechanical properties             |
|     |                   |                                 |                                                                           |                              | Mechanical stability                                                     | Suitable structure               |
|     |                   |                                 |                                                                           |                              | Adhesion                                                                  | (pore and porosity)              |
|     |                   | Joorabloo et al. [109]         | PVC (poly(vinylalcohol) cellulose)                                        | Heparinized Nano Zno/Carboxymethyl cellulose | Tensile strength                                                        | Food contact and food packaging |
|     |                   |                                |                                                                           |                              | Elastic modulus                                                           | Antimicrobial activity           |
| 2   | Food industrial   | Moreira et al. [110]           | Starch film                                                               | Nano-brucite                 | Modulus                                                                   | Food contact and food packaging |
|     |                   |                                |                                                                           |                              | Tensile strength                                                          | Antimicrobial activity           |
|     |                   | Şişmanoğlu et al. [111]        | Gum arabic                                                                | Nano iron (Fe)               | Antibacterial                                                             | Inhibited bacterial growth       |
|     |                   |                                |                                                                           | Nano SiO₂                    |                                                                            | Eco-friendly                      |


| Rafieian et al. [112] | Gluten | Carboxylate cellulose nanocrystal (CNCs) | Tensile strength | 60% |
|----------------------|--------|----------------------------------------|-----------------|-----|
| Ebrahimzade et al. [113] | Carboxyethyl cellulose (CMC) | Graphene nanoplates (GNPs) | Strain to break | 43% |
|                       |        |                                        | Water repelling nature | -   |
| Basu et al. [114]     | Chitosan | Poly-lactide nanoparticles (PLA)      | Tensile strength   | 5.4% |
| Kukuh et al. [115]    | Alginate films | CaSO₄ | Tensile strength | 42.34% |
|                       |        |                                        | Modulus of elasticity | 14.62% |
| Ilyas et al. [116]    | Sugar palm starch (SPS) | Sugar palm nanocrystalline cellulose (SPNCCs) | Young’s modulus | 69% |
|                       |        |                                        | Tensile strength   | 58% |
| Coativy et al. [117]  | Starch | Nanoclay | Tensile strength | ~160% |
|                       |        |                                        | Elastic modulus    | ~162.5% |
| 3 Industrial          | Medium chain length polyhydroxy Alkanoates (mcl-PHA) | Nanoclay (C15A) | Modulus | 840% |
| Chardron et al. [118] |        |                                        | Optical biosensors | .   |
|                       |        |                                        | Electromagnetic shielding | .   |
|                       |        |                                        | Magnetic characteristics | .   |
|                       |        |                                        | Electrochemical biosensors | .   |
|                       |        |                                        | Anticorrosion coating | .   |
|                       |        |                                        | Cling film | .   |
|                       |        |                                        | Reinforced, lightweight | .   |
|                       |        |                                        | . Non-toxic | .   |
| Material                        | Tensile strength | Modulus of elasticity | Applications                                      |
|--------------------------------|------------------|-----------------------|--------------------------------------------------|
| Wu et al. [119] POE (POE)      | 300%             | 300%                  | Good mechanical properties, Bioelectronics       |
|                                 |                  |                       | manufacturing applications, Cosmetic             |
|                                 |                  |                       | manufacturing process, Paper industry            |
|                                 |                  |                       | Flame retardancy purposes                        |
|                                 |                  |                       | Components in optics                             |
| Song et al. [120] Microcrystalline cellulose (MCC) Nano-SiO<sub>2</sub> | 21%              |                       | High absorbency, Cost-effective                   |
|                                 |                  |                       |                                                  |
| Yadollahi et al. [121] Carboxymethyl cellulose (CMC) Layered doubled hydroxide (LDH) | 148%             | 143%                  |                                                  |
| Kaboorani et al. [122] Polyvinyl acetate (PVA) Nanocrystalline cellulose (NCC) | 63%              | 70-155%               |                                                  |
| Abral et al. [123] Poly (vinyl alcohol) Ginger nanofibre | 65%              |                       |                                                  |
| Alcântara et al. [124] Polysaccharide -Starch (STH) -Alginate (ALG) -Chitosan (CHT) Fibrous clay mineral -Sepiolite -Palygorskite Young’s modulus Sepiolite Palygorskite | with STH 267% with CHT 344% with ALG 35% with STH 257% with CHT 322% with ALG 25% | Environment remediation, Toxicity up take systems, Absorbent for radioactivity removal, Eco-friendly materials production, Biodegradability, Antimicrobial activity, High absorbency, Non-toxic |

4 **Ecological**

| Material                        | Bioactivity | Antimicrobial | Production |
|--------------------------------|-------------|---------------|------------|
| Nathanael et al. [125] Hydroxyapatite (HAp) Titania (TiO<sub>2</sub>) | -           | -             | -          |
| Study                        | Material 1            | Material 2                  | Property 1       | Property 2       | Property 3       | Applications                                                                 |
|------------------------------|-----------------------|----------------------------|------------------|------------------|------------------|-----------------------------------------------------------------------------|
| Hazarika et al. [126]        | Wood-polymer Nanoclay | Flexural strength          | 20%              |                  |                  | Soil pollution control systems.                                              |
|                              |                       | Flexural modulus           | 20%              |                  |                  | Environmentally friendly antimicrobial applications                         |
|                              |                       | Tensile strength           | 38%              |                  |                  | Water purification                                                          |
|                              |                       | Tensile modulus            | 60%              |                  |                  |                                                                             |
|                              |                       | Harness                    | 20%              |                  |                  |                                                                             |
|                              |                       | Thermal stability          | -                |                  |                  |                                                                             |
| Yang et al. [127]            | Wheat gluten (WG)     | Lignin nanoparticles (LNPs)| Young' modulus   | 206%             |                  | Agricultural bags industry.                                                 |
|                              |                       |                            | Tensile strength   | 141%             |                  | Good mechanical properties.                                                 |
|                              |                       |                            |                  |                  |                  | Outdoor productions, agricultural equipment and products.                  |
| Kushwaha et al. [128]        | Chitosan              | Nanozinc oxide (ZnO)      | Tensile strength  |                  | 12.5%            | Eco-friendly                                                                |
|                              |                       |                            | Ultraviolet       |                  |                  | Renewable                                                                   |
|                              |                       |                            | resistance (UV)   |                  |                  | Cost-effective                                                              |
| Ali et al. [9]               | Polyurethane Nanoclay+empty fruit bunch | Compressive modulus | 120%             |                  |                  |                                                                             |
|                              |                       |                            | Compressive       |                  |                  |                                                                             |
|                              |                       |                            | strength          |                  |                  |                                                                             |
|                              |                       |                            | Thermal stability  |                  |                  |                                                                             |
| Arjmandi et al. [129]        | Montmorillonite (MMT) polylactic acid (PLA) | Cellulose nano whiskers | Ductility         | (10-90%)          |                  |                                                                             |
|                              |                       |                            | Modulus           |                  |                  |                                                                             |
|                              |                       |                            | Tensile strength   |                  |                  |                                                                             |
4. Advantages and disadvantages of bio and nano-composites

Using natural fibres as strengthening materials for polymer composites helps to protect the environment, with improvements in the waste stage as well as the processing and production stages. Bio-composites are biodegradable, tough, corrosive resistant, and extremely specifically strong; these materials also possess high creep resistance, wear resistance, and specific modulus [2, 130]. For example, the specific modulus (modulus/specific gravity) of flax (50) is higher than that of glass E-Fibre (28) [3]. The biodegradability of bio-composite materials is due to the nature of the reinforcement fibres, which allows the classification of the bio-composites as a healthy ecosystem. The improvements in stiffness and strength are realised in conjunction with high toughness due to controls on the bonding between layers and variance of the volume fraction of fibre. However, many factors affect such mechanical properties, including the fibre aspect ratio, transfer of stress at the interface, and orientation [3]. In particular, the uniform distribution of fibre in the matrix significantly affects the mechanical properties of bio-composites. Agunsoye and Aigbodion [131] used compounding and compressive modelling to produce bagasse-filled recycled polyethylene bio-composites; in total, two sets of composites were prepared using carbonised and uncarbonised bagasse particles. The bagasse filler ratios were 10 to 50 wt.%. The study showed that the major factor improving the mechanical properties was uniform distribution of bagasse particles, which offered an increase in hardness of around 240.64% and a tensile strength improvement of around 196% at 50 wt.% of carbonised bagasse filler in the polyethylene matrix. Superior corrosion resistance is required in applications such as orthopaedic implants, as elements such as chromium (Cr), cobalt (Co), and Nickel (Ni) have been found to be released from implanted bio composite materials due to corrosion in biological environments [8], and such materials may have toxic effects according to Wapner [132]. Utilising bio-composite materials (natural fibres plus polymers) is thus a recommended approach to increase chemical stability and corrosion resistance [3].

Generally, bio-composites are suitable for most low density products; however, there are several disadvantages to bio-composites: fibres may undergo degradation during processing; fibre distribution and orientation may reduce impact strength; degradation may arise when raw material are stocked for long periods of time, and low UV resistance may cause greater wear than in plastics [133]. The latter effect is due to the capability of UV energy to disassociate molecular bonds in the polymer matrix, which may cause the degradation of bio-composite materials [134]. Furthermore, nanoparticles with a hydrophilic nature increase surface energy and reduce wettability within the polymeric matrix [72]. Issues related to their fire resistance, inferior thermal properties, water absorption, degradability, and variability of properties with time and environmental conditions must thus be solved in the future for further successful advanced applications to be developed.

5. Conclusion

This work reviews trends in the use of nano-composite and bio-composite materials in advanced applications in numerous fields of engineering such as automobile, aviation, adhesive, electronic industries, and building, showing that nano-composite and bio-composite materials are now used in many significant applications, from high-tech systems such as aviation and aerospace, to common daily applications such as bio-sensors and food packaging. New high-performance materials have encouraged researchers to utilise bio-degradable elements to produce materials with potential ecological importance in terms of overcoming environmental challenges, offering a promising prospective for composites based on natural materials as opposed to industrial materials. However, several essential challenges remain:

- Interactions between nanoparticles at different length scales and matrix chains represent an essential challenge, and a more comprehensive understanding of these is required to tailor the properties of composites for certain applications.
- Uniform dispersion of nano-materials, good interfacial adhesion, and homogeneity in composite during the preparation process are critical, though these can be achieved through surface modification of nanoparticles, including using coupling agents.
Despite the availability of multiple experimental and research tools, the full assessment of toxicity of bio-composite materials utilised in biomedical applications remains daunting due to such toxicity depending on both production processes and functionalisation.

Further production of unique nano-composites with recyclable, lightweight, and biodegradable properties is required.

The overlap of bio-composite and nano-composite material provides opportunities to produce new materials with good stiffness, impact resistance, fatigue resistance, high specific strength, corrosion resistance, thermal conductivity, biodegradability, low relative density, and environmentally soundness at the waste stage; these composites may also allow the development of new materials with improved mechanical, thermal, and others functional properties based on combining bio-based polymer with natural fibres, though further research is required.

The utilisation of bio-nano-composites has improved several production aspects for materials such as biodegradability, antimicrobial activity, biocompatibility, mechanical properties, and suitable microstructure (pore and porosity) to make these composites suitable for tissue engineering and bone implant applications; however, the practical application of these requires further support.

Due to their significant bio-degradability, low relative density, high specific strength and renewability, bio-composite and bio-nano-composite materials are likely to be useful in multiple future applications; further research is thus required to determine the most promising areas of development.

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