Abstract: Functionally graded porous (FGP) nanocomposites are the most promising materials among the manufacturing and materials sector due to their adjustable physical, mechanical, and operational properties for distinctive engineering applications for maximized efficiency. Therefore, investigating the underlying physical and materialistic phenomena of such materials is vital. This research was conducted to analyze the preparation, fabrication, applications, and elastic properties of functionally graded materials (FGMs). The research investigated for both porous and nonporous synthesis, preparation, and manufacturing methods for ceramics, metallic, and polymeric nanocomposites in the first section, which is followed by deep research of the development of elastic properties of the above-mentioned materials. Main nano-reinforcing agents used in FGMs to improve elastic properties were found to be graphene platelets, carbon nanotubes, and carbon nanofibers. In addition, research studied the impact of nano-reinforcing agent on the elastic properties of the FGMs. Shape, size, composition, and distribution of nano-reinforcing agents were analyzed and classified. Furthermore, the research concentrated on modeling of FGP nanocomposites. Extensive mathematical, numerical, and computational modeling were analyzed and classified for different engineering analysis types including buckling, thermal, vibrational, thermoelasticity, static, and dynamic bending. Finally, manufacturing and design methods regarding different materials were summarized. The most common results found in this study are that the addition of reinforcement units to any type of porous and nonporous nanocomposites significantly increases materialistic and material properties. To extend, compressive and tensile stresses, buckling, vibrational, elastic, acoustical, energy absorption, and stress distribution endurance are considerably enhanced when reinforcing is applied to porous and nonporous nanocomposite assemblies. Ultimately, the review concluded that the parameters such as shape, size, composition, and distribution of the reinforcing units are vital in terms of determining the final mechanical and materialistic properties of nanocomposites.

Keywords: nanocomposites, functionally graded material, porous material, synthesis, fabrication, mechanical properties

1 Introduction

Nowadays, the manufacturing sector is evolving rapidly, and raw material demand is proportionally increasing. To tackle this, nanocomposite material usage has started to gain a reputation in many engineering sectors [1]. Nanocomposites are noncrystalline materials that are accepted as composites, which include nanoparticles of a material of dimensions smaller than 100 nm [2]. Utilizing nanocomposites
as nanobuilding blocks establishes brand-new materials with exceptional flexibility and enhanced physical features [3]. This study deeply analyzes different porous and nonporous nanocomposites and the main reinforcing units preferred to manufacture nanocomposites. The production process of a reinforced nanocomposite consists of adding reinforcement units (mainly as a form of nanofibers or nanotubes) to any composite materials [4]. To add, since different nanocomposite types have different structures, candidate reinforcing agents are required to be selected carefully to create a valuable chemistry between nanocomposites and reinforcing units. Nanocomposites are further divided into three main groups, which are [2,5] as shown in Table 1. Furthermore, processing and manufacturing methods of porous and nonporous nanocomposites (which will be discussed later in detail) play very important role in terms of acquiring demanded mechanical properties. Even though the main manufacturing methods are generally the same for every type of porous and nonporous nanocomposites, processing and synthesis procedures vary slightly and vastly for nonporous nanocomposites and porous nanocomposites, respectively.

1.1 Recent development of elastic properties of functionally graded porous (FGP) nanocomposites

In terms of materials sector, FGP materials can be cited as a prevalent example of development in the materials industry, which are specifically engineered to get utilized in many sectors [6]. This reputation of FGP nanocomposite materials is due to their incredible high surface area to volume ratio of consolidating phase. Toward the end of twentieth century, many initial prototypes of functionally graded material (FGM) were designed as thermal insulation coatings [7]. Nowadays, FGP nanocomposite materials are obtained via nanoscale addition of consolidation materials, which are generally carbon nanotubes (CNTs) and graphene platelets (GPLs) into metal, ceramic, or polymer matrices [8,9]. The addition of CNTs and GPLs considerably improves energy absorption properties of thin-walled rings, arches, beams, and plates [10,11]. Additionally, such materials have become commonly selected for a wide range of engineering applications such as lightness, electrical conductivity, energy absorption, and thermal management [12]. The unique physical and materialistic properties of FGP materials come from their specifically adjusted composition or microstructure shape toward specific operations. In an engineering aspect, developing of FGP was specifically required to reduce the stress fluctuations observed in composite materials. Moreover, FGP exhibit decreased transverse and in-plane stresses, minimized residual stress, elevated thermal resistance, minimized thermal conductivity, and elevated fracture toughness and resistance to interlaminar stresses [13,14].

However, detailed analysis performed by Yas and Rahimi [15] on FGP nanocomposites particularly on weight fraction, scattering patterns, size and geometry of platelets, and porosity allocation and coefficient revealed that the operation performance of GPLs is highly dependent on their geometry. Free vibration, buckling, and bending analysis of FG graphene nanoplatelets (GNPs)-reinforced nanocomposite under hygro-thermo-mechanical loads were presented by Yas and Rahimi [15]. Results highlighted that the assembly gets stiffer as the weight fraction of the GNPs increases, leading to an additional increase in the natural frequency and critical buckling stress. Elevated temperature and moisture decrease the stiffness, natural frequency, and critical buckling load [16]. Safaei et al. [17] conducted a research to investigate the effects of CNTs and porosity properties of CNT cluster/polymer porous nanocomposite sandwich plates (PNSPs). Additionally, mechanical and thermal stresses, geometry, elastic foundation parameters, and boundary conditions impact on the loading

| Ceramic matrix nanocomposites (CMNCs) | Metal matrix nanocomposites (MMNCs) | Polymer matrix nanocomposites (PMNCs) |
|--------------------------------------|------------------------------------|---------------------------------------|
| Porous CMNCs                         | Porous MMNCs                       | Porous PMNCs                          |
| Synthesis of porous CMNCs            | Synthesis of porous MMNCs          | Synthesis of porous PMNCs             |
| Synthesis of CMNCs                   | Synthesis of MMNCs                 | Synthesis of PMNCs                    |
| Schematics of synthesis              | Schematics of synthesis            | Pros and cons of synthesis methods    |
| Fabrication of porous and nonporous  | Fabrication of porous and nonporous | Fabrication of porous and nonporous   |
| CMNCs                                | MMNCs                              | PMNCs                                 |
| Schematics of fabrication            | Schematics of fabrication          | Schematics of fabrication             |
distributions, and the bending of PNSPs was examined. Authors highlighted that the functional grading of the core decreases deflection. Furthermore, the utilization of 5% volume fraction CNTs indicated negligible impact on the deflection of PNSPs due to the growth of CNT clusters.

1.2 Functionally graded graphene platelet-reinforced composites (FG-GPLRCs)

As previously mentioned, geometry is a vital issue in terms of free vibration and static bending performances of porous nanocomposites. Liu et al. [18] developed a design to investigate the weight fraction and geometry of FG-GPLRC spherical shells. Researchers created five distinctive models that have different GPL distributions, which are named as functionally ungraded, functionally grading type O (FG-O), functionally grading type X (FG-X), functionally grading type V (FG-V), and functionally grading type A (FG-A) and are displayed in Figure 1 [18].

As highlighted by the investigators, in terms of free vibration, the models FG-A (Figure 1, bottom right), FG-O (Figure 1, top right), and FG-X (Figure 1, top center), respectively, indicated an increase in the natural frequency magnitudes of torsional mode, breathing mode, and fundamental mode more efficiently. Nevertheless, in terms of static bending properties, the smallest radial displacement was observed on model FG-X (Figure 1, top center). Model FG-V (Figure 1, bottom left) possessed the lowest stress levels when different model assemblies of FG-GPLRC spheres were tested under a steady pressure acting from outside of the assembly.

As shown in Figure 2, a FG-GPLRC multilayer annular plate with an outer radius \( R_a \), an inner radius \( R_b \), and a thickness \( h \) is declared. The plate is reinforced of GPLs either uniformly distributed (U) or functionally graded (X and O) across the thickness. The dispersion type X with more amount of GPLs at the outer layers promotes higher linear frequency, followed by the types U and O. Contrarily, a conflicting tendency is detected for the nonlinear frequency ratio. The increase in temperature leads to an increase in nonlinear frequency ratio, however, decreased the linear frequency; those impacts were most considerable, consecutively, in type X, U, and O [19].

The impact of composition proportions on the elastic properties of functionally graded carbon nanofibers (CNFs)/
phenolic nanocomposites that were manufactured via combination of compression molding and powder stacking was scrutinized by Bafekrpour et al. [20]. Functionally graded nanocomposites (FGN) were designed to have eight layers with same thickness, two layers with 0 weight fraction, wt%, CNFs; two layers with 2 wt% CNF; two layers of 4 wt% CNF; and two layers of 16 wt% CNF. Four specimens were designed, which are FGN-1, FGN-2, FGN-3, and FGN-4 (Figure 3). FGN-1 was designed to have 16 wt% CNFs at the top and bottom of the beam, and mass fraction was decreased toward the center. FGN-2, 16 wt% CNF at the center and 0 wt% CNF at the top and the bottom. FGN-3, 16 wt% CNF at the top, 0 wt% CNF at the bottom, FGN-4 was designed to have 16 wt% CNF at the bottom, and 0 wt% CNF at the top. Investigators utilized finite element as well as analytic modeling to review composition-related variances on boundary conditions, loadings, and elasticity properties of nanocomposites. The authors concluded the dependency of elastic properties of the structure on the CNFs content of the thickness of the assembly. The investigation used a high proportion of CNFs parts, which have proven to improve Young’s modulus; however, the Young’s modulus of the final complete nanocomposite assembly still remained low even though building parts of the assembly have high CNF content. Kumar et al. [21] mentioned the consolidation of the structure by using CNFs is dependent on CNFs aspect ratio, balanced dispersion, CNFs misalignment [22], end-effects, and interlaminar bonding strength. Thermal residual stresses occurred during manufacturing are reported to have an impact on the overall mechanical features of the assembly [20,23]. Bafekrpour et al. [20] studied the tensile stress-strain and deflection curves of distinctive functionally graded nanocomposites and nongraded nanocomposites. The results highlighted that functionally graded nanocomposite with the highest CNF content (16 wt%) showed the best flexural properties, especially, the highest stiffness, whereas the nongraded nanocomposite exhibited the highest fracture load. This was explained by the reduction of toughness when high content of CNFs was utilized. Moreover, Mishra et al. [24] concluded the vitality of morphology of nanoparticles on determining the elastic properties. Flexural strength and modulus are highly dependent on the direction of the exerted load. In addition to this, spherical nanoparticles offer higher flexural strength while nanorods give higher flexural modulus to the structure.

1.3 FGP graphene platelet-reinforced nanocomposites

Chen et al. [25] have studied especially the nonlinear vibration and postbuckling load of multilayer FG-GLPRC beams. Porosity and reinforcement distribution were kept constant in each layer while the porosity coefficient and reinforcement weight fraction were varied for every layer.
The study was carried out investigating three different porosity distributions depicted in Figure 4, which includes both uniform and nonuniform porosity distributions. $E_1$ and $r_1$ are the highest Young’s modulus and mass density, respectively. $E_2$ and $r_2$ are the lowest Young’s modulus and mass density of the structure, respectively. The straight lines located at the top and the bottom indicate the intersection of the $E$, $r_1$ and $E_2$, $r_2$ with the corresponding pore size distribution of both uniform and nonuniform distributions. It is vital to emphasize the highest Young’s modulus and mass density values for nonuniform porosity cases (1 and 2) correspond to locations where porosity is more uniformly scattered. Additionally, for the steady porous distribution case, the middle plane was found to be the lowest magnitude of Young’s modulus and mass density and also the most vulnerable to stresses.

Another study carried out by Xu et al. [26] investigated the acoustical characteristics of the FGP graphene-reinforced nanocomposite plates. Different porosity and graphene distributions were used. Figures 5 and 6 have been added to illustrate both porosity and GPL distribution inside the nanocomposite assembly.

Investigation concluded the dependency of the acoustic properties on both porosity and reinforcement distribution such that the porosity considerably impacts stiffness, which has a direct influence on sound transmission loss values. Additionally, the impact of separation of reinforcement units (GPL) within the nanocomposite structure has been found to be controlling parameter in terms of acoustical features [26]. Moreover, different porous structures of cylindrical shells to find critical buckling values have been studied. Results concluded that the symmetrical distribution of the pores and GPLs through the thickness of the cylindrical shell proposes the optimal buckling values, whereas the physical size of the pores is inversely proportional with the buckling features of the structure [27].

Figure 7 obtained from an earlier study [28] illustrates the effect of distinctive porosity distributions (i.e., even and uneven) on deflection abilities of a square plate. Where $w_{\text{adim}}$ being the centralized deflection, which is the ratio of the central transversal displacement $w$, to the plate thickness $h$, ($w_{\text{adim}} = w/h$). Moreover, load parameter, donated by $P$ is defined by the formula $q_oa^4/E \times h^3$, where $q$ is generalized nodal displacements vector, $a$ is the square length, $E$ is the Young’s modulus, and $a$ is the porosity volume fraction where $0 < a < 1$. The research concludes higher displacement values for porous structures compared to nonporous structures. Additionally, even porosity distribution with higher $a$ value led to the greatest displacement [28].

1.4 Effects on the reinforcement of particle stiffness, geometry, and size

The main materials used in the reinforcement of nanocomposites are GPLs and CNTs. Even if both materials offer decent levels of reinforcement in terms of mechanically, elastically, and operational life, distinctions are present between the two reinforcement types. CNTs are proven to be more efficient than GPLs in terms of mechanical reinforcement in the case of symmetrical distribution, whereas GPLs propose more efficient reinforcement when random
distribution of reinforcement is the case. Furthermore, when the same physical magnitude and identical separation is utilized, CNTs offer considerably higher reinforcement than that of GPLs. This will cause a difference in bulk properties between CNT-reinforced and GPL-reinforced nanocomposites [29].

However, increasing the composition of soft/elastic micron/nanofillers enhances the impact toughness, however, decreases the Young’s modulus. Contrarily, increasing the composition micron/nano hard/rigid filler enhances impact toughness as well as Young’s modulus of polymer-based assemblies [30,31]. Additionally, the toughness and stiffness of the nanotube-reinforced polymer nanocomposites were obtained to be the functions of the elastic modulus of the nanotubes [32]. However, elastic modulus has been found to be increased slightly when the size of nanofillers utilized in the structure was decreased. Inversely, when the size of nanoparticles used in the structure decreased, the tensile strength of the structure has been found to be decreased [33]. Xu and Hoa [33] noted that the interfacial fracture toughness of carbon-fiber-reinforced epoxy/nanoclay nanocomposites was nearly doubled (85%) when four pieces of nanoclay were added to hundreds of epoxy by mass. Polit et al. [34] stated the impact of the weight dispersion pattern of GPLs on the stiffness, which was related to the porosity dispersion in metal foams. The places of the maximum shear stress and zero normal stress among the thickness are again related with porosity and GPLs load dispersion forms. Noteworthy variation in the buckling and fundamental frequency values was recorded when the amount of GPLs increased [35–37]. The characteristic and thickness proportion of GPLs significantly affect the operation performance of the beam. Feng et al. [38] studied the nonlinear static bending of multilayer functionally graded nanocomposite beams consolidated with GPLs. The study also discussed both the random and uniform distribution of GPLs. This research observed even a minor amount of GPL addition to the structure considerably decreases the static bending deflection of the beam further, this consolidation increases as the weight proportion of GPLs increases. As previously mentioned, this study also highlighted the importance of the GPL distribution pattern in terms of enhancing the bending properties of the beam.

Utilizing square GPLs with less single graphene layers and distributing more GPLs close to the top and the bottom surfaces of the beam instead of uniformly over the beam thickness is the most efficient method to effectively consolidate the stiffness and to decrease the deflection of the beam [39]. The normal stress break or disparity over the thickness direction of the beam drastically enhanced by increasing the overall number of layers. Utilization of ten layers can afford a decent approximation to the chosen GPLs dispersion, significantly decreased mismatch and comparatively less manufacturing cost. Arefi et al. [40] mentioned the nondimensional deflection of microplate is increased when the height-over-length ratio of the GPL is increased. Similarly, increasing the thickness-over-length ratio of GPLs when the volume of the graphene content kept constant, the stiffness of the plate decreases, which causes an increase in deflection. The increase in the GPL content increased the stiffness of the plate and decreased the interfacial strains. Increased porosity coefficients increased the axial stress. Additionally, increased porosity coefficients caused the increase in deflection, stress, and strains. Table 2 summarizes the effect of different parameters such as filler composition, filler size, filler weight distribution, and filler size on the operation performance of the final product in terms of impact toughness, buckling values, vibrational characteristics, elastic modulus, tensile strength, stiffness, and various stress properties [41].

2 Processing, fabrication, and applications of different porous nanocomposites

2.1 CMNCs

CMNCs are the mixing of one or several different ceramic phases to increase the wear resistance and thermal stability. Ceramics alone suffer from low toughness that results
in brittleness, which avoids the utilization of ceramics in many industrial applications. However, low toughness and brittleness problems are tackled when CMNCs used to offer more efficient and longer operation time at the area of utilization [2]. The reason why CMNCs are much stronger than ceramics alone lies at their structure where energy-absorbing materials such as fibers or particles are included in the ceramic matrix to decrease the brittleness and improve the durability against fracture [42]. Aluminium oxide ($\text{Al}_2\text{O}_3$) and silicon carbide (SiC) are the most common materials used in CMNCs. Examples of CMNCs can be given as $\text{Al}_2\text{O}_3/\text{SiO}_2$ and $\text{SiO}_2/\text{Ni}$ [5,43].

### 2.1.1 Porous CMNCs

Porous ceramic (nano)composites offer many benefits such as minor electrical and thermal conductivity, lightweight, low heat-to-mass ratio, increased specific surface area, reasonable hardness, resistance to wear, corrosion, and high temperature applications. The mentioned improved mechanical and material properties made porous ceramics significantly common in various engineering applications [44–46]. Processing of pores, fabrication of the porous matrix, and the physical dimensions of the pores have a great impact on the mechanical and material properties of the
manufactured ceramic composites. Recent progress on the
development of the pore control of the ceramics has devel-
oped a category in terms of separation of the pores with
regards to their physical dimensions. International Union of
Pure and Applied Chemistry (IUPAC) divided porous mate-
rials into three parts, which are represented in the descending
order as macroporous (diameter, “$\theta_{\text{macroporous}}$” > 50 nm),
mesoporous (50 > $\theta_{\text{mesoporous}}$ > 2 nm), and microporous
($\theta_{\text{microporous}}$ < 2 nm). Figures 8–10 illustrated the categor-
ization together with the main applications and manufac-
turing techniques with respect to definite pore diameters
as well as nanoscale porous structure images of open-cell
and closed-cell ceramics [47–49].

Although there are many recent processing techni-
ques of porous ceramics under development, the most
obvious processing methods can be stated as partial or
full sintering, replicas, sacrificial templates (fugitives),
and direct foaming [47,50,51]. Although the processing
techniques of the porous ceramics is slightly different
from nonporous ceramics, manufacturing techniques are
still the same. Especially, additive manufacturing (AM)
techniques, that is, chemical vapor deposition (CVD) is
the most common technique in terms of producing porous
ceramic structures, which are given in Table 3.

### 2.1.2 Processing and synthesis of ceramic matrix
nanocomposites (PCMNCs)

The most popular techniques utilized for PCMNCs and
porous ceramics are powder, polymer precursor, spray
pyrolysis, and chemical and physical vapor depositions.
Tables 4 and 5 include visualization of some common
strategies of manufacturing CMNCs. Additionally, Table
5 includes accessible schematics with labels of CMNC
synthesis.

![Figure 8: Porous structure of a closed-cell ceramic foam [47].](image)

Some main synthesis methods, such as powder, sol–gel,
precursoring, and pyrolysis techniques, have their unique
way of processing methods. Table 6 has been included to
emphasize the order of process as well as various stages of
the relative operation.

Every engineering manufacturing technique has its
own advantages and disadvantages. Table 7 has been
included to state and explain the relative advantages
and disadvantages of the synthesizing as well as proces-
sing systems of the CMNCs mentioned above in this article.

![Figure 9: Categorization of different pores with relative manufac-
turing techniques [46].](image)

![Figure 10: Categorization of different pores with relative manufac-
turing techniques [46].](image)
Table 3: Processing techniques of porous ceramics

| Synthesis method          | Description                                                                                                                                                                                                 | Ref.            |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| Sintering                | Synthesis process includes the reaction of relevant reactants with suitable precursors to obtain vapor phase nanoceramics                                                                                     | [47,50,51]      |
| Replica templates        | – Utilizes either synthetic or natural template, which is infiltrated through a ceramic suspension<br>– Later, when the mix is dried off completely, the template is detached leaving a replica of the initial template morphology                            | [47,50,51]      |
| Sacrificial templates, that is, freeze casting | – This method includes the so-called “pore former” or sacrificial to perform as a place keeper in the ceramic matrix<br>– Once the ceramic matrix consolidates, sacrificial is detached leaving empty pores behind<br>– To cite an example to this specific process, freeze casting uses ice crystals in ceramic matrix to form pores | [47,50–52]      |
| Direct foaming           | Utilizes gas bubbles that are intentionally trapped in the ceramic matrix during the slurry phase. When the ceramic slurry is dried off, the places occupied by gas bubbles take spherical pore shapes                                 | [47,48,50,51]   |

2.1.3 Fabrication of ceramic matrix nanocomposites (FCMNCs)

Fabrication of composites, nanocomposites, and porous and nonporous ceramic matrices are the same. The different ceramic materials are obtained at the synthesizing stage with different procedures (Tables 2 and 3). However, the final fabrication method, which can be implemented to mass production is the same for every ceramic composite branches. The most common fabrication techniques for CMNCs have been determined along with every process’s individual reactant arrangement and technique specification, which are presented in Table 8.

Table 8 mentions the main methods for fabrication of CMNCs. Additionally, Table 9 visualizes the above-mentioned fabricating strategies of manufacturing CMNCs. Accessible schematics with labels (if present for that process) of CMNC fabrication are presented below.

2.2 MMNCs

MMNCs are the mixing of ductile metal or alloy matrix and nanosized reinforcement materials. The cooperation between ductile metals and nanoparticles causes MMNCs to have an elevated ductility, toughness, strength, and modulus. Due to their superior materialistic and mechanical properties, MMNCs are widely utilized in automotive and aerospace industries [2]. Examples of MMNCs can be stated as iron–chromium (Fe–Cr)/Al₂O₃, nickel aluminium oxide (Ni/Al₂O₃), and Co/Cr (cobalt chromium) [5].

2.2.1 Porous MMNCs

Highly porous metals are attractive due to the high flow stress and toughness, solid mechanical formability, resistance to thermal degradation, and significant electrical and thermal conductivity features [108]. Porous structured metals are classified as lightweight, improved mechanical and material properties, with an additional energy absorption feature [109]. To be able to produce porous metals effectively and useful for specific engineering applications, various processing techniques has been recently used in the sector. Powder metallurgy, melt foaming, metallic fiber sintering, gas injection to metallic sheets, infiltration, metal deposition, and hollow sphere sintering are the main methods used for processing of porous structured metals [110]. Furthermore, lately innovated techniques to process and produce porous metallic structures are casting foaming (Aluminium foam) processes, precursor foaming, LOTUS-type foaming, and space holding processes. The most commonly utilized technique among these processes is the space holding process due to its ability in terms of allowing the regulation of the pore morphology of the porous metals [108–119]. Figure 11 shows the structure of porous aluminium (metal foam) obtained via space holder method. Additionally, this particular type of porosity is called a closed-cell structure, which can also be identified as metal foam. To extend, the closed-cell configuration in metals is more advantageous for many applications as it can endure under high pressure. Additionally, the closed-cell porous structures are nearly four times denser than the open-cell porous structures, which makes them more suitable for
Table 4: Indicating processing stages and synthesis methods for CMNCs

| Synthesis process         | Arrangement                                                                 | Process                                                                                      | Ref.               |
|---------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|--------------------|
| Sol–gel                   | Silica oxide/nitrite (SiO2/Ni), zinc oxide/cobalt (ZnO/Co), titanium oxide/iron (TiO2/Fe2O3), lanthanum oxide (La2O3) | – Addition of water and condensation reactions of an organic/inorganic molecular precursor dissolved inorganic solutions | [53–57] |
|                           |                                                                               | – Three-dimensional (3D) polymers that contain metal-oxygen bonds are obtained at the end of mentioned reactions |                    |
|                           |                                                                               | – The process is followed by ventilation operation to remove excess liquids and to obtain a solid material, which is then subjected to thermal operations for strengthening |                    |
| Powder                    | Al2O3/SiC                                                                     | – Choice of materials that will be used in the process (mainly selected as powders mainly small dimensions, uniform, and purified) | [55,56] |
|                           |                                                                               | – Mixing of the solution in organic or aqueous solutions by using a technique called wet ball milling or a attrition and milling |                    |
|                           |                                                                               | – Drying by utilizing lamps and special ovens or by freeze drying |                    |
|                           |                                                                               | – Heat-treatment processes are applied to strengthen the obtained solid material. Such processes are generally hot pressing, gas pressure sintering, slip casting or injection molding, and pressure filtration |                    |
| Polymer precursor         | Al2O3/SiC, silica nitride/SiC                                                 | – Addition of silicon polymeric precursor to the matrix material. Pyrolysis of the solution with the help of microwaves, leading to the consolidation particles | [55,56,58] |
|                           |                                                                               | – This specific type of solid-synthesis technique includes mixing of mechanical and chemical facts at a macroscopic scale. It is feasible via this method to obtain a required product utilizing solely mechanical action such as the application of elevated pressure to the reactants at an ideal temperature | [59–65] |
| Mechanochemical            | Acid base/magnesium TiO2, beta phase CP/magnesium TiO2/magnesium oxide        | – Vapor phase synthesis process includes the reaction of relevant reactants with suitable precursors to obtain vapor phase nanoceramics, which then can be deposited on the required surface easily via various methods such as CVD | [65–68] |
|                           | For oxide–oxide composites                                                    | – Gas phase condensation method is also a common way of vapor phase processing |                    |
|                           | For nonoxide–oxide composites                                                |                                                                             |                    |
|                           | Al2O3/zirconium diboride/ZrO2, Al2O3/titanium diboride                         |                                                                             |                    |
|                           | For nonoxide–nonoxide composites                                             |                                                                             |                    |
|                           | Boron carbide/SiC, niobium carbide/nioium diboride                           |                                                                             |                    |
| Vapor phase               | ZrO2/SiO2, TiO2/vanadium pentoxide                                           |                                                                             |                    |
|                           | For oxide–oxide composites                                                   |                                                                             |                    |
|                           | For nonoxide–oxide composites                                                |                                                                             |                    |
|                           | Silicon nitride/SiC                                                           |                                                                             |                    |
| Self-propagating high     | Silicon nitride/titanium nitride, silicon nitride/molybdenum silicide,       | – Synthesis of required material is accomplished by using heat obtained from the chemical reaction of the material during processing | [65,69–73] |
| temperature synthesis     | silicon nitride/silicon nitride, silicon nitride/titanium nitride            |                                                                             |                    |
| (SHS)                     | For nonoxide–nonoxide composites                                             |                                                                             |                    |
|                           | Silicon nitride/titanium nitride, silicon nitride/titanium nitride            |                                                                             |                    |

(Continued)
harsher operations. However, comparatively high density of closed-cell structures makes them infamous for lightweight engineering applications \[120,121\]. Nevertheless, the processing method utilized to attain porous structure on the metallic materials decides the nature of the porous matrix. Moreover, porous structure within any metallic materials plays an important role in deciding the ultimate physical and mechanical properties. Hence, categorization of porous metals leads to a separation of the above-mentioned processing techniques into following sets \[108\]:

- **Isolated porosity**
- **True metal foam**
- **Foam precursor**

### Table 4: Continued

| Synthesis process | Arrangement | Process | Ref. |
|-------------------|-------------|---------|------|
| Spray decomposition/combustion | zirconium diboride–SiC–zirconium carbide–zirconium silicide | - The reacting substances will alter to resultants throughout the combustion reaction, which will be observed straight after the reaction initiates. | [65,74–77] |
|                      | For nonoxide–oxide composites; Al2O3/SiC, mullite/titanium diboride | - Another name of the process is solution combustion | |
| Coprecipitation synthesis | For oxide–oxide composites Al2O3/zirconium dioxide; cerium(v) oxide–metal2oxide3 and metal2oxide–zinc dioxide; Gamma–iron(II) oxide–TiO2/ZrO2/magnesium aluminate | - The process includes initiation and developing of automaintained heating reactions at an either aqueous or sol–gel atmospheres. | [65,78–81] |
|                      | - Distinctive nanomaterials can be synthesized via this method. | |
|                      | - Control of reaction conditions greatly affects the yield. | |
| Surface modification | For oxide–oxide composites Aluminum oxide/zirconium dioxide; aluminium oxide/yttrium aluminate; zirconium dioxide/gadolinium oxide; lanthanum aluminium (11) oxide (18); and calcium hydroxyapatite/iron(III) oxide/mullite/aluminium oxide | - The process is considered to be an alternative to similar sol–gel processing as it is also utilized chemical ways to mix oxides together. | [65,82–87] |
|                      | - The reaction includes dissolution of reactants in a traditional solvent and a following addition of precipitating agent to obtain a homogeneous solid material. | |
|                      | - The precipitation solution is further decomposed at elevated temperatures to obtain aimed oxide. | |
|                      | - Surface-modification processes act as a bridge between powder mixing and chemical methods. | |
|                      | - The aim of the surface modification is to enhance the properties of the powders which will be used in the mixing process. | |
|                      | - This process not only increases the efficiency of the overall synthesis but offering an enhancement in terms of control of the ultimate physical and morphological condition of the obtained microstructure. | |

Pores are isolated within the metal structure. Sometimes referred as “dilute porosity.”

- True metal foam
- A gas phase generates a group of physically in contact bubbles divided by thin metal membranes. Hence, the natural structure of the specific porous system tends to be closely celled.

- Foam precursor
- An already located polymer foam (i.e., polyurethane) is utilized to produce the structure of the metal.
Table 5: The schematic of the synthesis methods for CMNCs. The processes, which schematics are not included, are either chemical reactions or do not have any processing unit.

Schematic of sol–gel processing

Schematics of powder processing for various materials
Table 5: Continued

Schematic of SHS unit

Schematic of the spray decomposition

Schematic of the coprecipitation synthesis
Porosity created by packing

- Individual porous elements are attached together to form an assembly, which has high porosity content.

Porosity created by phase change

- Phase changes of a single distinct phase to many phases, mainly gas, leads to the creation of a porous structure.

Regular lattices

- A steadily porous structure, generally created by repeated deposition of new layers, is attached to, or embedded in, porous elements or porous alloys.

2.2.2 Processing and synthesis of metal matrix nanocomposites (PMNCs)

The most popular techniques utilized for PMNCs and porous metals are precursoring, pyrolysis, CVD, physical vapor deposition (PVD), infiltration and solidification, and sol-gel processes. Table 10 summarizes the processing stages for precursoring (1) powder, (2) sol-gel, (3) polymer precursor, and (4) gas phase pyrolysis obtained from an earlier study [56].

Table 6: The processing stages for (1) powder, (2) sol-gel, (3) polymer precursor, and (4) gas phase pyrolysis obtained from an earlier study [56]

| Powder (1) | Sol–gel (2) | Polymer precursor (3) | Pyrolysis (4) |
|------------|-------------|-----------------------|---------------|
| Ceramic powder + nanoparticles | Ceramic precursor sol + nanoparticles | Ceramic powder + polymer | \[
\left(\text{SiCH}_3\right)_{12}\text{NH} + \text{NH}_3 \text{ (in air)}
\] | Reaction chamber \((1,000^\circ\text{C}/\text{N}_2)\) |
| Ball milling \((\text{solvent})\) | Coating/drying | Amorphous \((\text{SiN})_x\) | Furnace \((1,500^\circ\text{C} / 6\text{ h/argon})\) |
| Drying | Hydrothermal processing | Heat treatment \((1,350^\circ\text{C}/4\text{ h/argon})\) | Mixing with sintering aids |
| Hot pressing | Sol | Pyrolysis | Hot pressing |

2.2.3 Fabrication of metal matrix composites

| Phase changes of a single distinct phase to many phases, mainly gas, leads to the creation of a porous structure. |
|---|
| Porosity created by phase change |
| Regular lattices |
| Individual porous elements are attached together to form an assembly, which has high porosity content. |
Table 7: Benefits and disadvantages of processes

| Name of the process | Benefits | Drawbacks | Ref. |
|---------------------|----------|-----------|------|
| Sol–gel             | – Not complex  
                      – Low temperature application  
                      – Adaptable  
                      – Multiple matrices achievable  
                      – Specific usage toward composite materials  
                      – No impurities on the final product  
                      – Formation of 3D metal-oxygen bonds | – The amount of porosity is low when compared to mixing strategy  
                      – Shrinkage is more often that affects the performance | [53–57] |
| Powder              | – Not complex  
                      – Easy to operate | – Requires elevated working temperature  
                      – Energy intensive  
                      – High cost  
                      – Dispersion of particles is not very accurate  
                      – Formation of unwanted phases during production | [55,56] |
| Polymer precursor   | – Feasibility of producing better particles  
                      – More accurate/efficient scattering of particles within the matrix structure | – Production of inhomogeneous materials because of accumulation of fine products | [55,56,58] |
| Vapor phase         | – Allows synthesis of ultrapurity nanoparticles  
                      – Size, shape, and internal structures are controllable  
                      – Reaction rate can be modified | – Does not produce a high yield, which makes this technique not suitable for industrialization | [67] |
| SHS                 | – High purity can be achieved  
                      – Energy efficient process  
                      – Can be used to produce high-quality metal matrices  
                      – Dense products  
                      – Short production rate  
                      – Not complex | – Energy-intensive process but consumption is high  
                      – Costly | [69,93] |
| Spray decomposition | – Homogeneous products  
                      – Elevated purity  
                      – Fast and easy process  
                      – No complex apparatus required  
                      – Low energy consumption  
                      – Suitable for magnetic metal oxide production processes | – Requires a lot of expensive solvents that increase the capital cost of the process  
                      – Mass production is challenging  
                      – Challenging to control the process parameters and variables that affect the outcome | [65,94] |
| Coprecipitation     | – Simple application  
                      – Cheap reactants  
                      – Low poisonous waste products  
                      – Easy to control process parameters  
                      – Modifications on final homogeneity and particle surface is available  
                      – Low energy and temperature application  
                      – No organic solvent is required  
                      – Elevated quantity of magnetic products can be obtained by using this method | – Application on uncharged particles is not possible  
                      – Slow process and time consuming  
                      – Cannot be applied if there is a significant mismatch on the precipitation rates of the solvents  
                      – Distribution of the particles is not efficient, which makes coprecipitation prone to aggregation | [95–97] |
| Mechanochemical     | – Suitable for nonstoichiometric halides synthesis at low temperatures  
                      – Eliminates the risks of high temperature applications such as thermal decomposition and high pressure | – Unwanted products can be produced which can lead to contamination of the final product. Oxidation is inevitable | [59,98,99] |
### Table 8: Distinctive manufacturing ways of CMNCs

| Name of the process         | Arrangement of the process | Technique                                                                 | Ref.                        |
|-----------------------------|----------------------------|---------------------------------------------------------------------------|-----------------------------|
| Hot pressing                | SiO\textsubscript{2}/CNT    | Scattering of CNTs and silicon oxide glass powders into C\textsubscript{2}H\textsubscript{5}OH, mixing, and ultrasonic action | [55,56,100]                 |
|                             | SiC/CNT                    | Drying off and hot-pressing sintering at pure nitrogen medium              |                             |
|                             |                            | Stirring and addition of SiC and CNTs together                            |                             |
| CVD or spray pyrolysis      | Al\textsubscript{2}O\textsubscript{3}/CNT | By anodizing CNTs into its holed walls, preparation of alumina matrix is achieved | [55,56,101,102]            |

(Highly used for porous ceramic manufacturing)

| Catalytic decomposition     | Al\textsubscript{2}O\textsubscript{3} /CNT | Utilization of C\textsubscript{2}H\textsubscript{2} over Al\textsubscript{2}O\textsubscript{3} powder soaked within the structure of the iron catalysts | [55,56,103]                 |

| Solvothermal process        | Iron three oxide (Fe\textsubscript{3}O\textsubscript{4})/CNT | Scattering of CNTs in ethylenediamine utilizing ultrasonic process         | [55,56,104]                 |
|                            |                                                        | Mixing of an iron three urea complex and heating in a Teflon-lined oven with an internal temperature kept steady at 200°C for 50 h |                             |
|                            |                                                        | Cooling down to an optimal temperature                                      |                             |

### Table 9: The schematics of the manufacturing processes of CMNCs. The process schematics, which are not included are either chemical reactions or do not have any process units

#### Schematics of standard hot-pressing technique
![standard hot-pressing technique](image)

#### Schematic of CVD
![schematic of CVD](image)

#### Schematic of catalytic decomposition method
![schematic of catalytic decomposition method](image)
implemented to mass production is the same for every metallic composite branches. The following table illustrates the FMMNCs. A brief explanation of the process application as well as corresponding advantages and disadvantages is also depicted in Table 13.

In the previous section, the FMMNCs were given and explained in Table 13. Table 14 includes visual representation of the schematics with labels of the above-mentioned fabrication methods of MMNCs.

2.3 PMNCs

Fillers are the nanosized particles (nanofillers) used in PMNCs, which are categorized as 1D – linear, 2D – layered, and 3D powder. The link between polymer matrix and nanofiller at a molecular stage has an impact on the attraction between nanocomposites. As a result, supply of minor amount of nanofiller with dimensions smaller than hundred nanometers to matrix causes alteration on the overall composite material properties. Materialistic properties of PMNCs are elevated thermal stability, enhanced abrasion resistance and elevated barrier capacity (reduced gas permeability) [149]. To cite examples of PMNCs, thermoplastic/thermoset polymer/layered silicates, polyester/Tin oxide can be given [5]. Usage areas of PMNCs in daily life and industry are packaging, power tool housing, fuel and solar cells, and fuel tank [2].

2.3.1 Porous PMNCs

Porous polymers are becoming one of the most promising material group which are being started to utilize in almost every engineering sector. This research interest on such materials are due to their ability to own properties of both porous materials and polymers in a sole structure. Porous polymers have large surface area, exceptional physiochemical properties, ease of production and processing. Furthermore, porous polymers can be dissolved within a solvent and directly processed while maintaining the porous structure which is not possible to achieve in any other porous structures [150,151].

Figure 12 illustrates the scanning electron microscope image of macro porous polyurethane. The method utilized to produce this type of porous structure is known as gas foaming, which is the most popular technique. Various gaseous products obtained during chemical reactions can be used at some point in the manufacturing of the porous polymer which can be removed later to construct porous structure. In the production of macroporous polyurethane shown in Figure 12 the porous structure was obtained by removing the carbon dioxide molecules produced during the chemical reactions. This specific porous structure can be named as an open-cell structure, which is proven to be less dense and more flexible than the closed-cell structures [121,152]. Moreover, FGP polymer structures can be specifically designed to illustrate responsive properties with an additional ability to alter the pore structure relative to the engineering application. Porous state of the polymers can be altered between closed and open state when environmental exposure is the case. Additionally, since the structure of the porous polymers are organic and includes light components, the overall mass of the structure is significantly reduced, providing additional advantage of light-weighting [150,153,154]. Porous polymers are generally categorized by their size, physical shape, pore shape and dimension, spread of interconnectivity, and ultimate amount of porosity. The application which the porous polymer structure is supposed to be used is a deciding factor in terms of what kind of porous structure and mechanical properties of the polymer will have [155]. To effectively consider the porous polymer structure and respective structure’s preparation and fabrication techniques, it is vital to divide the porous polymer structures into intersections. IUPAC has produced a template to classify the porous polymers relative to their pore size which is previously mentioned in the porous CMNCs section of this report. The union has agreed to separate porous structures into three distinct classes named as; microporous, macroporous and mesoporous. Note that, the porous structure of the polymer has a strong correlation with its manufacturing technique.

- **Microporous polymer structures** ($\phi_{\text{microporous}} > 2\, \text{nm}$)
  - The most important property of such polymers is high flexibility. This unique feature leads to efficient adsorption as well as cohesion applications. In
| Process | System | Procedure for MMNCs | Ref. |
|---------|--------|---------------------|-----|
| Spray pyrolysis | Iron/magnesium oxide, tungsten/copper | A thin film is positioned via spraying an occupied solution onto a high temperature surface. The reaction between the solution and the heated surface resulted in a chemical compound | [2,55,91,122] |
| Liquid metal infiltration | Lead/copper, lead/iron, tungsten/copper, niobium/copper, niobium/iron, aluminium–fullerene | This process is an alternative for squeeze casting. However, the infiltration operate fibers/particles via liquid metal is provided in the form of high-pressure inert gas, and the operation is performed in a vacuum atmosphere. A previously shaped template is located into a split metal die in the required shape of the part. Die and metal chamber is evacuated and high-pressure gas (i.e., Ar) is applied to the melt compartment. Gas pushes the molten metal into the die to infiltrate the fiber. The pressure is kept steady until the solidification completes | [2,55,122,123] |
| Rapid solidification | Aluminium/lead, aluminium/A/zirconium (A = silicon, copper, nickel) iron alloys | rapid solidification process process is a substitute to traditional casting methods for the processing of aluminium–copper alloys. The process includes the fast extraction of heat of a high-temperature molten metal to solidify. It is an elevated solidification rate process and can lead to noticeable variations | [2,55,122,124] |
| Rapid solidification with ultrasonics | Aluminium/ SiC | This new method includes the measurements of the interfaces during phase changes. The process is carried out during the fast solidification process. The operation requires echoes reflected from interfaces to track the | [2,55,122,125] |
Table 10: Continued

| Process                        | System                              | Procedure for MMNCs                                                                                       | Ref.                  |
|-------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------|-----------------------|
| High energy ball milling      | Copper–Al₂O₃                        |  Milling of the introduced reinforcing powders until the essential size is produced, that is, nanosized particles | [2,55,97,122]         |
| CVD/PVD                       | Aluminium/molybdenum, copper/tungsten, copper/lead | PVD:                                                                                                    | [2,55,97,122,126]     |
| Sol–gel, colloidal (chemical processes) | Silver/gold, iron/SiO₂, gold/iron/gold | CVD:                                                                                                    | [2,55,122,127,128]     |
|                               |                                     | Colloidal:                                                                                               |                       |
|                               |                                     |  Metal pieces are utilized to lead the chemical reduction of salts in a solution                          |                       |
|                               |                                     |  Reinforcement of the dry piece                                                                       |                       |

(Continued)
addition to this, empty spaces inside the polymer structure can promote effective interconnectivity [151].

- **Mesoporous polymer structures** ($2 \text{ nm} < \theta_{\text{mesoporous}} < 50 \text{ nm}$)
  - These specific porous polymers are manufactured via either soft or hard templating. The fundamental applications which mesoporous polymers are utilized are catalyst applications, synthesis of membranes, separation, and purification. Mesopolymers are proven to be used as organic semiconductors for osmosis and photocatalytic operations [151,156].

- **Macroporous polymer structures** ($\theta_{\text{macroporous}} > 50 \text{ nm}$)
  - Macropolymers are produced via cross-linking copolymerization of vinyl and divinyl monomers in a noble diluent. The diluent used during the mentioned reaction, which can be either linear polymer, nonsolvent or solvent, is the key factor in terms of determining the porous structure of the macroporous polymer. By being similar to microporous and mesoporous polymers, there is also a strong correlation between porous structure and the manufacturing method of macroporous polymers. To cite examples, freeze drying, porogenation, microemulsion formation, and gas blowing methods can be utilised to produce macroporous polymers. [150,151].

According to the Berro et al. [151], the most common preparation methods of porous polymers are; gas foaming, phase (immersion precipitation, chemically and thermally reaction driven phase separation) separation, small liquid drops templating (emulsion, bicontinuous micro emulsion and breath figures templating), colloidal crystal templating, templating via self-assembled structures, molecular imprinting and biotemplating utilizing natural biological templates. These methods are tabled in the following section. Production of pores on polymer structures, corresponding advantages and disadvantages are included in Table 15.

### 2.3.2 Processing of polymer matrix nanocomposites (PPMNCs)

The previous section explains the processing and preparation of porous PMNCs. Similarly, the following section is the categorization of the porous polymers. The main processing techniques are sol–gel, various polymerization methods, intercalation, and sacrificial template utilization. Table 16 summarizes the processing techniques of porous polymer nanocomposites with corresponding system arrangements and process procedures.
Table 11: Various processing method schematics of MMNCs. Processes for which schematics are not included are either chemical reactions or do not have any processing units.

Schematic of spray pyrolysis with ultrasonics

Schematic of liquid metal infiltration process

Schematic of rapid solidification with ultrasonics
The previous section explains the processing techniques of PMNC systems. The following section summarizes the advantages and disadvantages about the mentioned PPMNCs in Table 17.

2.3.3 Fabrication of polymer matrix nanocomposites (FPMNCs)

Fabrication of polymeric, nanocomposites, and porous and nonporous ceramic matrices are the same. The different polymeric materials are obtained at the synthesizing stage with different procedures (Tables 15 and 16). However, the final fabrication method, which can be implemented to mass production is the same for every polymeric composite branches. Table 18 illustrates different FPMNCs. A brief explanation of the process is available together with the relative advantages and disadvantages of every manufacturing process.

The previous section explains the main fabrication methods of PMNCs with brief explanation as well as advantages and disadvantages. The next section is the visuals of the above-mentioned manufacturing processes utilized during the manufacturing of PMNCs. Table 19 depicts the schematics of the processes explained previously in Table 18.
2.4 Applications of porous nanocomposites in various engineering sectors

The application of porous nanocomposites offers improved mechanical and material properties of the engineering assemblies. Distinctive engineering sectors including biomedical, electrical and electronics, aerospace, marine, mechanical, and energy storage are greatly demanding constant development and innovation on the material usage in many engineering applications for improved efficiency and longer service life. To cite, Pinkert et al. [186] studied the spatial separation of the metal

### Table 12: MMNC processing techniques along with the relative advantages and disadvantages

| Process | Benefits | Drawbacks | Ref. |
|---------|----------|-----------|------|
| Spray pyrolysis | – Efficient production of very good quality, fine, shaped, and homogeneous particles | – Not a scaled-up method (low product levels) | [2,55,123] |
| | – Cost-effective method | – Oxidation of sulfides can be a major issue in an air atmosphere | |
| | – Does not need high-quality reagents | – The growth temperature is challenging to modify | |
| | – Surfaces, morphologies and shapes can be efficiently controlled by modifying operation conditions and supplies | – Expensive when large batches required to be produced | |
| Liquid metal infiltration | – Complex shaped part production is available | – Uncontrollable porous structures | [55,122,123] |
| | – Lower pressure levels | – Not very efficient mechanical properties, that is, low wear resistance | |
| | – Lab-scale production and scaled-up industrial productions are available | – Bonds between the particles are not strong | |
| | – Minimized contact time between the matrix and reinforcements | | |
| Rapid solidification | – Extension of the solid solubility | – Solely operated for metal nanocomposites | [55,122,124] |
| | – Production of metastable crystalline phases | – Agglomeration and inhomogeneous dispersion of grains | |
| | – No microsegregation during solidification | | |
| | – Good cellular structure | | |
| | – Enhanced grain size and shape | | |
| | – Easy and efficient technique | | |
| Rapid solidification with ultrasonics | – Efficient dispersion without agglomeration | Not specified | [55,122] |
| | – New technique | | |
| High energy ball milling | – Relatively inexpensive | – Challenging to classify with respect to particle size | [55,122,123,133] |
| | – Ease of scaling up to produce large volumes | – Causes surface contamination | |
| | – Homogeneous mixing of materials | | |
| | – Uniform scattering of reinforcement particles | | |
| CVD/PVD | CVD: | – Costly and complex process | [55,122,134] |
| | – High-purity products with uniform grains can be produced | – Relatively low yield | |
| | – Capable of producing high-density and pure materials | | |
| | – Uniform depositions | | |
| | – Good adhesion and reproducibility | | |
| | PVD: | | |
| | – Improved mechanical and material properties | | |
| | – Compatible with all inorganics and most organics | | |
| | – Eco-friendly process | | |
| | Sol–gel: | – Costly and complex | [55,123] |
| | – Efficient, effective, and versatile | – Challenging to coat complex structured shapes | |
| | – High-purity final products | – Relatively low yield | |
| | – Low-temperature application | – High porosity | |
| | – Produces large and stable surfaces | – Reduced wear resistance | |
| | Colloidal: | – Low internal bonding strength | |
| | – Simple process | | |
| | – High chemical homogeneity | | |

### Review of fabrication, preparation and application of FGP nanocomposite materials

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| Process name                        | Application                                                                 | Advantages                                                                 | Disadvantages                                                                 | Ref.     |
|------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------|
| Stir-casting                       | Stirring mechanism is integrated into the molten metal and constant stirring is performed to ensure a steady dispersion of nanoparticles within the molten matrix | － Versatile － Cheap － Not complex － Very compatible with aluminium and magnesium matrices | － Cluster can be formed between nanoparticles because of high surface area, which can lead to elevated van der Waals forces among nanoparticles － High porosity as a result of air bubbles trapped in the mixture due to stirring － Wetness of the solid particles cannot be controlled within the molten matrix | [135–137] |
| Disintegrated melt deposition (DMD) | Molten composite called “slurry” is produced similar to stir casting process. The obtained slurry is transported through a pouring nozzle where high temperature (up to 1,200 K) noble gas is present (i.e., Ar). After the pouring operation is finalized, the slurry is transferred onto metal substrate. The final form of the nanocomposite is an ingot, which then can be reformed to a required final shape via hot extruding process | － Highly compatible with magnesium metal － Eliminates excessive oxides and waste metals | － Energy-intensive process － High amount of heating is required for elevated noble gas temperature － High cost | [137–140] |
| Semisolid casting (SSC)            | Highly accurate die casting method. The nanocomposite material is transported into a mold hole in a semiliquid/semisolid state, and the casting process takes place at mold cavity compartment | － Lowered energy consumption compared to other methods － No postprocessing is required － Finish quality of the part is very good － Porosity levels in SSC structure is negligible | － Producing materials with complex shapes (i.e., circular, spherical) is challenging | [137,141] |
| Power metallurgy (PM)              | This technique uses solid materials to cast. The solid reinforcement and matrix materials (mainly in powder form) are blended until a required composition is achieved. The process is followed by a squeezing process to obtain a “compaction.” The casting process is terminated by sintering via microwave energy. To ensure the quality of the product is decent, sometimes equal channel angular pressing or extrusion processes can be applied at high temperatures | － Capable of producing complex shapes (i.e., near net shaped) － Adjusting the volume of nano-reinforcing units within the metal matrix is possible with this method － Mass production and elevated batch volumes is achievable | － Equipment of PM are costly only viable in the case of mass production － Raw material cost is high － Sometimes density of identical parts can vary due to uneven compression － Mechanical properties of PM parts are not very good compared to machined parts | [137,142] |
| Friction stir processing (FSP)      | FSP process is very similar to friction stir welding, which is very common in many manufacturing sectors to integrate nanomaterials into a metallic matrix to obtain bulk or surface nanocomposites. A groove of required metal matrix is filled with nano-reinforcements. A rotating pin-less tool attached to the substrate is used to close the groove trapping | － New technology － Efficient process － Energy consumption is not very high － Quality process － Very compatible with magnesium and aluminium components, which leads to enhanced mechanical properties | － Surface of the final product is not quality. － Distribution of nano-reinforcements is not uniform due to uneven stirring | [137,143,144] |
hydroxide nanoparticles within the porous carbon matrix. Efficient distribution of the nanoparticles within the functionalized porous carbon network revealed improved energy density levels, which leads to an efficient supercapacitor utilization in electronics. Moreover, porous magnetic nanocomposites used in biomedical engineering showed enhanced mechanical properties especially higher tensile strength. Scanning electron microscope (SEM) images illustrated improved internal connection between macroporous and microporous structures, which is the reason of improved strength. Magnetic Fe₃O₄ nanoparticles are utilized for abovementioned biomedical engineering applications due to its reasonable water absorption properties as well as healthy antimicrobial possessions. [187]. To sum up, different nanocomposite assemblies are used in different engineering sectors. To cite an example, porous MMNCs are highly preferred in medical, aeronautics, marine, transportation (land and air transport), and military protection applications [188]. Moreover, porous PMNCs are mainly used in food packaging, coating, adhesion, drug delivery, electric, and electronic applications [189]. However, porous CMNCs are mainly utilized in industrial, civil, and energy absorbing applications [190]. The differences among the application areas of three nanocomposites originates from the variations between morphological, atomical, and bonding structures. Table 20 has been added to illustrate distinctive porous nanocomposite materials along with their relative engineering sector.

### 3 Numerical, mathematical, and computational modeling review

A research conducted by Ansari et al. [210] studied geometrically nonlinear static bending of FG-GPLRC porous plates. Four distinctive porous dispersion plan and patterns were selected, and material characteristics were deduced by using closed-cell Gaussian random field (GRF) scene, the Halpin–Tsai micromechanical model, and the rule of mixture [15,18]. To process the data on computer, authors used virtual work principle and higher-order shear deformation theory (HSDT) derivations in matrix form. Variational differential quadrature (VDQ) and finite elemental methods (VDQ–finite element modeling [FEM]) numerical approach was used. The problem domain was divided into finite elements and VDQ selection method was exploited for every finite element model. Authors used the mentioned procedure to investigate the impact of porosity and GPL dispersions. Resulting matrix equations were solved with the help of the pseudo arc-length continuation algorithm.
Table 14: Various fabrication methods of MMNCs

Schematics of stir-casting

![Schematic of stir-casting](image1)

Schematic of disintegrated melt deposition

![Schematic of disintegrated melt deposition](image2)

Schematic of powder metallurgy

![Schematic of powder metallurgy](image3)

(Continued)
This study highlighted the tendency of VDQ–FEM propose efficiency for solving problems. Another study carried out by Yas and Rahimi [15] examined the variation of thermal buckling of FGP nanocomposite beams under distinctive temperatures by using generalized differential quadrature method (GDQM). Different nanofillers, scattering patterns, and porosity allocations were studied. GRF was used together with closed-cellular solids to obtain Poisson’s ratio and correlation among porosity coefficient and mass density. Halpin–Tsai micromechanics modeling was utilized to determine elastic modulus of the nanocomposite. Arshied et al. [211] utilized the GRF model method for closed-cell cellular
| Technique                          | Production method of pores | Advantages                                                                                       | Disadvantages                                                                                     | Ref.            |
|-----------------------------------|-----------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|-----------------|
| Direct templating                 | Space obtained via elimination of the templates. Mainly chosen for soft materials                 | - Easy                                                                                           | - Requires sacrificial templates                                                                     | [150,157]        |
|                                   |                              | - The manipulation of the meso/macroporous structure is possible                                | - Complex and costly for scaled up production                                                      |                 |
|                                   |                              | - Functional grading is achievable                                                               | - Not very efficient pore production                                                               |                 |
|                                   |                              | - The manipulation of the meso/macroporous structure is possible                                | - Cannot be utilized effectively for hard materials                                               |                 |
|                                   |                              | - Functional grading is achievable                                                               | - Not very efficient pore production                                                               |                 |
| Block-copolymer self-assembly     | Space obtained via removal of sacrificial component, morphology regeneration, and vesiculation   | - Customized pore structure and arrangement                                                      | - Not a very effective method for mass production                                                  | [150,158]        |
|                                   | Two different polymers bonded covalently to self assemble to form a specific structure in nanoscale-customized pore size | - Suitable for complex structures such as stimuli responsive assemblies                          | - Expensive                                                                                       |                 |
| Direct synthesis                  | Microporous                  | - High surface area of this structure enables permanent porosity                                | - There is only one way that the monomers for this process can be produced                        | [150,159]        |
|                                   | Links between monomers are hyper-cross linkable                                                  | - Pore structure can be customized by customizing the monomer structure used in the porous assembly | - Expensive process and raw materials                                                              |                 |
|                                   |                              |                                                                                                | - Control of the resultant pore structure is challenging                                           |                 |
|                                   |                              |                                                                                                | - Low reaction rate                                                                                |                 |
|                                   |                              |                                                                                                | - Low yield                                                                                       |                 |
|                                   | Mesoporous/macroporous       | Via phase generation                                                                            | - Microporous structures are complex to achieve via this method                                   | [150,159]        |
|                                   |                              | - Ease of control of the process and the resultant structure                                     | - Low reaction rate                                                                                |                 |
|                                   |                              |                                                                                                | - Low yield                                                                                       |                 |
| High internal phase emulsion polymerization | Space obtained via changing of the internal phase                                             | - Elevated porosity levels (75–95%)                                                             | - Low surface area                                                                                 | [150]            |
|                                   |                              | - Exceptional void and frame structure are achievable                                             | - Weak mechanical properties                                                                      |                 |
| Interfacial polymerization (IP)   | IP takes place between two nonmiscible solutions causing spaces to occur due to the removal of the micelle | - Very compatible in terms of synthesizing nanocapsules                                         | - Pore structure control is challenging                                                           | [150,160]        |
| Breath figures                    | Water droplets bombarded from a cold region to warm surface led to the production of micro/nanopores via condensation of water droplets from the templates | - Simple                                                                                         | - Producing nanopores (<100 nm) is challenging                                                    |                 |
solids for the porous matrix characteristics and effective feature so from porous nanocomposite was obtained by Halpin–Tsai along with extended rule of mixture micromechanics model. Shear deformation impacts were considered by using the first-order shear deformation theory (FSDT). Energy method was used to derive equations and solved by generalized differential quadrature (GDQ).

To understand the thermoelastic manners of sandwich plates with porous polymeric core and CNT clusters/polymer nanocomposites, Safaei et al. [17] used total energy function along with mesh-free strategy together with two-plate theories to deduce the leading thermoelastic equations. To monitor the temperature dependency of the CNT clusters/polymer nanocomposite, Eshelby–Mori–Tanaka’s method was operated. Yang et al. [212] utilized FSDT to consider the transverse shear strain and Chebyshev–Ritz approach to discretize the displacement fields. Leading equations were extracted and then solved to deduce critical uniaxial,
The advantages and disadvantages of PMNC processing methods

| Name               | Benefits                                                                 | Drawbacks                                                                 | Ref.   |
|--------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|--------|
| Sol–gel            | - Not complex                                                             | - High amount of shrinkage                                                 | [55,162]|
|                    | - Low operation temperature                                               | - Relatively reduced amount of voids                                       |        |
|                    | - Versatile                                                               |                                                                          |        |
|                    | - Efficient chemical homogeneity                                          |                                                                          |        |
|                    | - Stoichiometry control                                                   |                                                                          |        |
|                    | - Elevated purity (clean/pure samples)                                    |                                                                          |        |
|                    | - Successful in terms of producing inorganic–organic hybrids              |                                                                          |        |
| Template synthesis | - Suitable for batch production                                           | - Exclusively compatible with water soluble polymers                       | [55,162]|
|                    |                                                                          | - Contamination                                                           |        |
| Melt intercalation | - Not complex                                                             | - Applicable together with the use of polyolefins, which are not environmentally friendly products | [55,162]|
|                    | - Cheap                                                                   |                                                                          |        |
|                    | - Simple procedure                                                        |                                                                          |        |
|                    | - Eco-friendly                                                            |                                                                          |        |
|                    | - Can be integrated to industrial manufacturing (suitable for batch production) |                                                                         |        |
| In situ intercalative polymerization | - Not complex                                                                 | - Not suitable for many applications                                        | [55,162]|
| from solution      | - Controllable dispersion of nanoparticles within the polymer precursors   | - Challenging to regulate intragallery polymerization                      |        |
|                    | - Homogeneous reactant polymers                                           |                                                                          |        |
|                    | - Reduced polarity polymer reactants                                      | - Expense                                                                 | [55,162]|
|                    |                                                                          |                                                                          |        |

baxial, and shear-buckling stresses, as well as the natural frequency of the plates with distinctive porosity and GPL dispersions. Moreover, to scrutinize material properties of graphene-reinforced nanocomposites, similarly, Liu et al. [18] used Halpin–Tsai and rule of mixtures. In addition, free vibration and bending equations of nanocomposite were derived with the help of 3-D elasticity theory together with the state space method. Jalal et al. [213] proposed usage of big data approach for an efficient design of composite structures, which mainly considered functionally graded carbon nanotube-reinforced nanocomposites. The materialistic features of the nanocomposites were deduced via Eshelby–Mori–Tanaka method. Following, researchers compared two methods of using big data approach, which are mesh-free method and optimized neural network (ONN). Robust mesh-free technique was utilized to extract vibrational frequencies, impact of CNT alignment and aggregation. Six parameters (geometry dimensions, composite core, nanocomposite layer, volume fraction of CNTs and clusters, volume fraction of changing exponent) included a total of 15,625 data sets, which are followingly analyzed by ONN. ONN results were found to be very consistent and confirmed the suitability of ONN’s usage for enormous data analyzing. Furthermore, utilization of ONN is nearly a thousand times faster relative to mesh-free method with negligible amount of simulation error [214]. Yaacoubi et al. [215] studied loading distributions and shifting in sandwich plates, which reinforced with functionally graded nanocomposite face sheets was tested by FSDT built on mesh-free strategy. The assembly was treated as Winkler–Pasternak elastic model, and the nanocomposite was consolidated with three distinctive CNTs. Molecular dynamics (MD) study at nanoscale and Halpin–Tsai were utilized to deduce the elastic constants of the assembly. The adjustment of boundary conditions was vital. This was accomplished by utilizing moving least squares (MLSs) to approximate the displacement field and the transformation technique.

Temperature plays an important role on the nonlinear free vibration of edge-cracked graphene nanoplatelet (GNP)-reinforced composite laminated beams [216]. Supposing GNP fillers were dispersed randomly and thermal field was distributed uniformly, material properties of the GPLRNC was found via micromechanical models. Loading and intensity coefficients were deduced via FEM. Karman-type geometric nonlinearity with respect to FSDT was used to derive crack motion equations. The bending stiffness of the cracked section was modeled via massless rotational spring model, and finally, differential quadrature technique was utilized to extract both linear and nonlinear natural frequencies of the ruptured GPLRNC beams.
Table 18: The manufacturing methods utilized to produce PMNCs as well as relative advantages and disadvantages

| Manufacturing method | Description | Advantages | Disadvantages | Ref. |
|----------------------|-------------|------------|---------------|------|
| Wet lay-up           | Required composite resin to be transported into a mold and treated for consolidation. Can be carried out either via spray pistol or manually by hand | – Simple  
– Low cost | – Poor final mechanical property products  
– Nonuniform distribution of the resin  
– Excessive voids on the final product | [164] |
| Pultrusion            | Nanofibers are pulled by a high-temperature dye. During the pulling, a steady pressure is applied to melt the resin and to deposit the melt into the fibrous reinforcing agent | – Cheap  
– Continuous  
– Fast  
– Efficient alignment of fibers can be regulated via optimization of the manufacturing parameters | – Process wastes can accumulate at the edges and can cause disorders (unexpected final product shapes)  
– Excessive void production  
– Constant cross section is hard to obtain | [164,165] |
| Resin transfer molding (RTM) | RTM is a closed molding application where polymer matrix is deposited over preplaced reinforcing fibers, which is followingly placed onto a mold | – Cheap  
– Compatible with high batch production | – Requires advanced equipment for tooling and design (i.e., expensive)  
– Complex application  
– Complex parts are challenging to obtain  
– High resin viscosity can block the flow  
– Possible dryness at certain places  
– Nonuniform dispersion of resin is possible for some specific shapes | [164,166,167] |
| Vacuum-assisted RTM  | Integrated RTM process where vacuum is utilized to improve resin flow and to decrease void formation. Layered composites are insulated with a plastic material. Resin is directed to the wrapped parts to fill the voids between the composite layers | – Reduced resin flow blockage  
– Low-cost application for high-volume production  
– Huge and complex parts can be produced  
– Enhanced final surface and better mechanical property products  
– High fiber volume fraction | – Possible dryness at certain places  
– Nonuniform dispersion of resin is possible for some specific shapes | [164,168,169] |
| Filament winding     | Resin impregnated fibers are wrapped over a mandrel at distinctive angles to form a piece | – Complex parts can be produced  
– Viscosity problems are eliminated  
– Cost effective | – Limited to the shape of the part, only certain structured shapes can be produced  
– Crossovers points can decrease the quality of the final product  
– Size of the fiber used affects the performance of the process, that is, large geometry fibers can increase the production time  
– Highly expensive  
– Elevated capitalized cost | [164] |
| Fiber placement technology | Prepreg plies can be located automatically and quickly with good geometry in a short period of time | – Automated  
– Fast  
– Accurate | – Size of the fiber used affects the performance of the process, that is, large geometry fibers can increase the production time | [164,170] |
| Autoclave processing | Open molding process where molded piece is enhanced with the help of the vacuum, heat, pressure, and inert gases. The molded piece is then transported in a plastic bag and the trapped air is discharged via an exhaust. This eliminates air inclusions and volatiles. Followinglly, heat, gases, and pressure within the autoclave cures and consolidates the material | – Widely used industrial method  
– Complex and high-quality parts can be produced  
– Both thermosets and thermoplastics can be manufactured with reduced thickness and reduced porosity  
– Homogeneous parts | – Highly expensive  
– Elevated capitalized cost | [164,171] |

(Continued)
Nguyen et al. [39] proposed an effective numerical method to investigate and regulate geometrically nonlinear responses of the FGP plates consolidated with GPLs integrated with piezoelectric segments. The methodology was the utilization of iso geometric analysis (IGA) based on the Bezier extraction and the C zero type HSDT ($C^0$–HSDT). By using the Bezier extraction, the original nonuniform rational B-Spline (NURBS) control meshes were converted into the Bezier elements, which lead to receive the standard numerical process such as the finite element method (FEM). The mechanical shift field was estimated based on the $C^0$–HSDT, whereas the electric potential was supposed to be the function of the thickness of every single piezoelectric sublayer. The FG plate contains the inner pores and GPLs distributed in the matrix either uniformly or nonuniformly rendering distinctive patterns along the thickness of the plate. Moreover, to manipulate dynamic feedbacks, two piezoelectric layers were attached to the top and the bottom faces of the plate. The geometrically nonlinear equations were solved by the Newton–Raphson iterative technique and the Newmark’s time integration scheme. Furthermore, a steady shift and velocity response control methods were implemented to effectively monitor both nonlinear dynamic and static feedbacks of the plate. With the help of this strategy, structural damping, based upon a closed loop control with piezoelectric instruments, was scrutinized.

Set of tables below has been included to categorize various modeling of nanocomposites, which have been extensively discussed above. Distinctive categorization has been done for different nanocomposite types. To cite an example, Table 21 illustrates the modeling classification of nanocomposite beams. Similarly, consequent Tables 22 and 23 illustrate modeling parameters for nanocomposite plates and for nanocomposite shells, respectively.

Categorization of nanocomposite in terms of analysis model, mathematical model, numerical approach, equations derivation method, and computational algorithm (if used in the study). Table 22 depicts the modeling classification of nanocomposites plates.

Grouping of nanocomposites in terms of analysis model, mathematical model, numerical approach, equations derivation method, and computational algorithm (if used in the study). Table 23 depicts the modeling classification of nanocomposites shells.

Table 24 includes the summary of the key assumptions and the main distinctions of mechanical models, which have been previously discussed in Tables 21–23 in detail.
**Table 19:** The schematics of the various FPMNCs

| Schematics distinctive wet lay-up methods | Schematics of pultrusion |
|------------------------------------------|-------------------------|
| Hand lay-up                              | Resin injection pultrusion |
| Spray lay-up                             | Conventional pultrusion process |

Hand lay-up

1. Woven reinforcement
2. Gel coat

Spray lay-up

1. Air pressured resin
2. Chopper gun
3. Optional gel coat

Compartments of resin infusion-pultrusion:
- **A1:** Resin flow front (resin enters the pultrusion unit from this point)
- **A2:** Middle section (resin is at both liquid and gel states in this compartment)
- **A3:** Solidification zone (where temperature decreases and resin solidifies)

(Continued)
Table 19: Continued

Schematic of RTM

[Image of schematic of RTM]

Schematic of vacuum-assisted RTM

[Image of schematic of vacuum-assisted RTM]
Review of fabrication, preparation and application of FGP nanocomposite materials

Table 19: Continued

Schematics of filament winding process

[180,181]

Schematics of fiber placement technology

[177,182]
Table 19: Continued

Schematic of autoclave processing

[183]

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Table 20: Various nanocomposites and their respective usage in the engineering sector

| Nanocomposite                                      | Applications in engineering                                                                 | Ref.    |
|----------------------------------------------------|---------------------------------------------------------------------------------------------|---------|
| C/MoS₂                                             | Novel electrode material for supercapacitors                                                | [191]   |
| Ag/carrageenan–gelatine hybrid hydrogel            | Biological applications including tissue engineering, regenerative medicine, antimicrobial, anticancer, and drug delivery | [192]   |
| Fluoroalkyl end-capped oligomeric                  | Biomedical, pharmaceutical, coatings, electronics, optics, and diagnosis                    | [193]   |
| Polyhedral oligomeric silsesquioxanes (POSS)-based polyamide | Thermosets, thermoplastics, drug delivery, solid polymer electrolytes, membrane applications (desalination, gas separation, food packaging, and automobile (fuel tanks) | [194]   |
| POSS-based biocompounds                            | Dental applications, drug delivery, and tissue engineering                                  | [194]   |
| Organo/rubber/clay nanocomposites                  | Automotive, flame retardant, and lightweight                                               | [195]   |
| Polymer/silica/colloidal                           | Gas barrier coatings, catalysts, and chromatography                                         | [18]    |
| Graphene based                                     | Energy (batteries, fuel cells, PVs), environmental                                          | [196]   |
| ZnO                                                | Domestic and industrial                                                                    | [197]   |
| Polymer (PMNC)                                     | Solar cells, sensors, and conductance thin films                                            | [197]   |
| Layered double hydroxide sheets                    | Cosmetic (allowable permeable membrane production)                                        | [198]   |
| Polymer pencil (porous graphite material)          | Electrode utilization, electrochemical analysis of materials                                | [199]   |
| Porous graphene nickel oxide                       | Supercapacitors, energy storage, and regenerative systems                                  | [200]   |
| Porous ZnO/C                                       | Several energy storage (fuel cells) and environmental (used as catalysts in many vital reactions such as hydrogen evolution reaction during water-splintering process) applications | [201]   |
| Carbon nanofiber polydimethylsiloxane (CNF/PDMS)  | Sensing applications. Can be utilized as piezoresistive sensors in numerous engineering sectors | [202]   |
| Carbon coated MnO                                  | Utilized as anode in electrochemical applications                                          | [203]   |
| Porous silica–graphene                             | Environmental-aimed applications. Removal of contaminants such as oil, heavy metal, organic solvent, and dyes from water | [204]   |
| Honeycomb-like porous zinc carbodiimide-based nanocomposites | Electronic applications. Used to manufacture asymmetric supercapacitor cells               | [205]   |
| High porosity-reduced graphene oxide/NiCo₂S₄       | Electrode materials for electrochemical applications (reduced graphene oxide being anode active and NiCo₂S₄ being cathode active material) | [206]   |
| Multifunctional Fe₃O₄/N₂ doped-porous carbon nanocomposite | Used as catalyst during purification/separation reactions. Used in water treatment and medicine | [207]   |
| Porous FeMnO                                       | Supercapacitor electrode applications                                                      | [208]   |
| Copper–porous silicon (Cu/PSi)                     | Can be used as an electrode as well as sensor for identifying formaldehyde during electrochemical applications | [209]   |

4 Conclusion

The research analyzed the synthesis, processing, preparation, and fabrication as well as elastic properties of FGP materials, along with the mathematical, numerical, and computational modeling. Manufacturing processes of every material differs naturally. One thing should be emphasized is that every material type including ceramics, metals, and polymer has a different processing technique for relative porous structures. However, the final fabrication method of both porous and nonporous structures is still the same after the raw material has been obtained via preprocessing. Additionally, sol–gel processing was found to be most popular processing technique for both porous and nonporous structures and it can be utilized for every type of nanocomposites (ceramic, metal, polymer). Metal nanocomposite structures are costly due to high temperature applications and production, whereas polymers are the most famous and chosen material for engineering application unless the application is an extreme temperature application. The addition of nanoreinforcing agents to the above-mentioned materials takes place during the synthesis and preparation, which were proven to enhance the mechanical and materialistic properties of the assemblies.

The effect of nanofillers of nanofillers were discussed and classified. The research highlighted the importance of nanofiller parameters on the elastic properties of the functionally graded nanocomposites. The tendencies found are as follows:

- Increasing the nanofiller composition in the structure increases the impact toughness of the nanocomposite and
Table 21: The classification of different modeling for beams

| Nanocomposite type | Analysis type                          | Mathematical model                                                                 | Numerical approach | Equation derivation method (including numerical method)                                                                 | Computational algorithms used                     | Ref.       |
|-------------------|---------------------------------------|------------------------------------------------------------------------------------|--------------------|---------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|-----------|
| Beam              | Static bending                        | GRF, Halpin–Tsai micromechanical along with the rule of mixtures                   | FEM                | HSDT in matrix form solved by VDQ                                                                                         | Pseudo arc-length continuation algorithm          | [15]      |
| Beam              | Thermal buckling                      | Halpin–Tsai micromechanical, GRF along with closed-cellular solids for matrices   | FEM                | Energy method and FSDT solved by GDQ                                                                                       | Not specified                                   | [213,221,222] |
| Beam              | Nonlinear free vibration and postbuckling analysis | Halpin–Tsai micromechanics along with rule of mixture | Not specified      | Timoshenko beam theory and von Karman type arbitrary further solved by Ritz method                                          | Direct iterative algorithm                        | [223,224] |
| Beam              | Nonlinear flexural bending            | Halpin–Tsai micromechanics                                                        | FEM                | Shear deformation theory based on trigonometric function, von Karman, potential energy principle                           | Direct iteration algorithm                        | [225,226] |
| Beam              | Dynamic instability                   | Halpin–Tsai micromechanics                                                        | Not specified      | Differential quadrature method used to derive Mathieu–Hill equations, which was finally used together with Bolotin’s method | Layer-wise model                                 | [227,228] |
| Beams             | Dynamic                               | Eshelby–Mori–Tanaka                                                               | FEM                | Timoshenko and Euler–Bernoulli beam theories used, and equations derived via Hamilton’s method together with Newmark’s method | Not specified                                   | [229]      |
| Beams             | Buckling and postbuckling             | Halpin–Tsai micromechanics                                                        | Not specified      | FSDT and differential quadrature method                                                                                   | Not specified                                   | [230–232] |
| Multiwalled beams | Free and forced vibration             | Halpin–Tsai micromechanics                                                        | FEM                | Timoshenko beam theory                                                                                                      | Not specified                                   | [233]      |
| Laminated beams   | Bending stiffness and frequencies     | Micromechanical                                                                   | FEM                | Karman type geometric nonlinearity and FSDT. Solved by differential quadrature technique                                | Not specified                                   | [25,217]  |
Table 22: The classification of different modeling for plates

| Nanocomposite type | Analysis type | Mathematical model | Numerical approach | Equation derivation method (including numerical method) | Computational algorithms used | Ref. |
|--------------------|---------------|-------------------|-------------------|---------------------------------------------------------|-------------------------------|------|
| Plates             | Free vibration | Halpin-Tsai along with rule of mixtures | FEM | FSDT | Layer-wise model | [234,235] |
| Plates             | Thermoelastic  | Eshelby–Mori–Tanaka | Not specified | Total energy function and two-plate theories | Mesh-free strategy | [17,236–238] |
| Plates             | Transverse shear strain | Halpin-Tsai, rule of mixtures | Not specified | Chebyshev–Ritz method and FSDT | Not specified | [25] |
| Plates             | 3D free vibration and bending | Halpin–Tsai micromechanical model along with rule of mixtures | Not specified | State-space-based differential quadrature method | Not specified | [239] |
| Plates             | Vibro-acoustic | Halpin–Tsai micromechanical | Not specified | Hamilton's principle and third-order shear deformation theory. Navier method and Rayleigh's method | Not specified | [240–242] |
| Plates             | Statistical analysis including free vibration, mechanical properties | Halpin–Tsai micromechanical approach | FEM | HSDT | Analysis of variance used to derive empirical/mathematical model | [243–245] |
| Plate              | Control of nonlinear responses of piezoelectric FGP plates | Eshelby–Mori Tanaka | IGA | Bezier extraction and HSDT. Solved by Newton–Raphson iterative procedure and Newmark’s time integration scheme | NURBS control meshing | [39,246–248] |
| Plate              | Acoustic      | Halpin–Tsai micromechanical with GRF | FEM | Hamilton's principle, Modal theory, and Rayleigh's integral method | Not specified | [26] |
| Plate              | Bending and vibrational | Halpin–Tsai along with rule of mixtures | FEM | Not specified | Parametric study via FEM software | [249] |
| Quadrilateral plate | Nonlinear and free vibration | Classical plate theory | Not specified | Differential quadrature with transformed weighing coefficients. Von-Karman strain–displacement | Direct iterative algorithm ANSYS | [250–252] |
| Sandwich plates    | Stress distributions/forced vibration | Halpin–Tsai | FEM | FSDT | Mesh-free strategy | [214,253–255] |
| Nanocomposite type | Analysis type                  | Mathematical model        | Numerical approach | Equation derivation method (including numerical method)                          | Computational algorithms used                                                                 | Ref. |
|-------------------|--------------------------------|---------------------------|--------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------|
| Spherical shells  | Free vibration and bending    | Halpin–Tsai multiscale    | Not specified      | 3D elasticity theory with state space method                                       | Layer-wise analytical approach                                                              | [18] |
| Shells            | Mechanical uncertainties on the free vibration properties | Halpin–Tsai micromechanical | FEM                | HSDT solved via Fourier differential quadrature (FDQ)                             | Finite element analysis software ABAQUS                                                      | [256]|
| Conical shells    | Free and nonlinear vibration  | Not specified             | Not specified      | Hamilton's principle. FSDT, GDQM used to solve Donnell-type differential equations (DEs) | Parametric study                                                                           | [257–261]|
| Cylindrical shells| Semianalytical postbuckling   | Halpin–Tsai               | Not specified      | FSDT, von Karman, Fourier series and VDQ                                          | Pseudo-arc length continuation and load disturbance approach                                | [262–265]|
| Cylindrical shells| Free vibration                | Halpin–Tsai micromechanical along with rule of mixtures | Not specified      | Hamilton's principle, FSDT                                                         | Parametric study                                                                           | [258,266]|
| Shallow shells    | Free vibration and static bending | Halpin–Tsai               | FEM                | Hamilton's principle, HSDT, Navier method                                           | FEA software ANSYS                                                                         | [267–269]|
| Cylindrical shells| Semianalytical wave characteristics | Halpin–Tsai along with rule of mixtures | Not specified      | FSDT, higher order spectral elements, Hamilton's principle. Fourier transforms     | Not specified                                                                             | [270,271]|
| Shells            | Double curved shallow shell/laminated composite plate | CNT added design          | Not specified      | Shear deformation shell theory. Galerkin and fourth-order Runge–Kutta method        | Mesh-free method and ONN                                                                      | [215]|
|                  | Free vibration and nonlinear dynamic response | Eshebly–Mori–Tanaka       | Finite element analysis |                                                                                   | Not specified                                                                             | [245,272–275]|
|                  |                                | Reddy's higher order      |                    |                                                                                   |                                                                                             |      |
Endurance to bending can be increased when nano-

Increasing the number of layers in laminated

Square nano-

Decreasing the physical size of nano-

Increasing the physical size of nano-

Increasing the amount of GPLs, increases buckling

HSDT Used to perceive the impact of shear deformation on the structures. Suitable for vibrational analysis. Used to derive elasticity and dynamic equations

Halpin–Tsai Utilized to estimate the elastic properties of composites by considering the topography and the arrangement of the filler (reinforcement) and the composite matrix. This method relies on Hartree–Fock system, which is also known as self-consistent system

Mori–Tanaka An efficient field theory, which relies on Eshelby’s elasticity approach for both inhomogeneous and infinite media. This method can be utilized to deduce mean internal stresses within a composite structure, which has inclusions due to strain variation. To be able to calculate the modulus of the nanocomposites, both matrix and the filler are required to have 3D elastic parameters

Runge–Kutta An efficient strategy to resolve the initial value problems of DE. This approach can be utilized to develop higher order numerical method without requiring high-order derivatives

GDQM Used to solve governing equations obtained from the mechanical modeling

FSDT Used to perceive the impact of shear deformation on the structures. Assumes shear strain is constant throughout the thickness. Suitable for thinner structures

HSDT Used to perceive the impact of shear deformation on the structures. Suitable for analysis of both thick and thin structures

Table 24: Key assumptions and the main distinctions of mechanical models

| Mechanical modeling/equation derivation method | Brief explanation of theories, which are extensively used in studies | Ref. |
|---------------------------------------------|---------------------------------------------------------------|-----|
| Hamilton’s principle | Assumes a system, which obeys Newtonian route and changes state from time to time | [276] |
| Rule of mixtures | Utilized to predict properties of composite materials. Assumes properties of composites are functions of the volume-weighed mean of the matrices or distributed phase’s properties | [277] |
| Halpin–Tsai | Utilized to estimate the elastic properties of composites by considering the topography and the arrangement of the filler (reinforcement) and the composite matrix. This method relies on Hartree–Fock system, which is also known as self-consistent system | [278,279] |
| Mori–Tanaka | An efficient field theory, which relies on Eshelby’s elasticity approach for both inhomogeneous and infinite media. This method can be utilized to deduce mean internal stresses within a composite structure, which has inclusions due to strain variation. To be able to calculate the modulus of the nanocomposites, both matrix and the filler are required to have 3D elastic parameters | [279] |
| Runge–Kutta | An efficient strategy to resolve the initial value problems of DE. This approach can be utilized to develop higher order numerical method without requiring high-order derivatives | [280] |
| GDQM | Used to solve governing equations obtained from the mechanical modeling | [281] |
| FSDT | Produces efficient solutions especially for vibrational studies | [282] |
| HSDT | Used to perceive the impact of shear deformation on the structures. Suitable for analysis of both thick and thin structures | |

Young’s modulus \((E)\) of the soft/elastic nanocomposites. Contrarily, this will lead to a decrease in the Young’s modulus values of hard/rigid porous nanocomposites.

- Increasing the amount of GPLs, increases buckling values and stiffness. Furthermore, it decreases static bending properties and led to an increase in interfacial stresses.
- Increasing the physical size of nanofillers, increases the Young’s modulus \((E)\) of porous structures.
- Decreasing the physical size of nanofillers, decreases the tensile strength of the porous structures.
- Endurance to bending can be increased when nanofillers are distributed uniformly.
- Square nanofillers distributed close to the top and the bottom of the beam structures increases stiffness and decreases deflection.
- Increasing the number of layers in laminated (sandwich) structures enhances the stress distribution.
- The physical proportion as well as the geometrical shape of the nanofiller greatly influences the bending properties. Increasing the height-over-length ratio of rectangular nanoporous filler increases deflection, increasing the thickness-over-length ratio of rectangular nanofiller decreases stiffness as well as deflection resistance.

The studies conducted to analyze various properties of porous nanocomposites includes broad mathematical and mechanical modeling assumptions. Modeling review highlighted some worth mentioned tendencies, which are specified below.

- Halpin–Tsai approach is the most common modeling type utilized in many applications including beams, plates, shells for many kinds of analysis including stress distribution, static bending, thermal buckling, thermoelastic, shear strain, vibrational, bending stiffness, and frequencies.
  - Rule of mixtures for composites, GRF, and micromechanical models are the methods used along with Halpin–Tsai.
- The most common numerical method used in FGM sector is FEM among reviewed studies.
- HSDT and FSFDT were the most common equation derivation methods.
  - In some cases, Chebyshev–Ritz method, total energy function, two-plate theory, energy functional method, 3D elasticity with state-space method, Karman type geometric nonlinearity, and Bezier extraction were used as well.
  - VDQ and GDQ approaches were the most common techniques to solve derived equations.
- Pseudo-arc length continuation algorithm, mesh-free strategy, layer-wise analytical approach, and MD approach were computer-aided methods used for analysis.
- NURBS control meshing optimization technique can be used along with iso geometric numerical method to control the nonlinear response of piezoelectric in FGP nanocomposite plates.

Apart from modeling and nanofiller properties, some other vital parameters were found that can greatly influence the operational lifetime and properties of the nanocomposites. These factors are given below.
- Elevated temperature and moisture led to the decrease in stiffness, natural frequency, and critical buckling load of porous nanocomposites.
- Functional grading of the core decreases deflection, which decreases flexibility.
- Elastic properties of the structure are greatly dependent on the CNF content distribution along the thickness direction of the assembly.
- Thermal residual stresses occurred during manufacturing, due to shrinkage and high temperature difference between operations, decreases the overall operational lifetime performance by increasing the interlaminar stresses.
- FGP nanocomposites with higher CNF content exhibits better flexural properties especially, higher stiffness.
  - Structure with higher CNF content have more tolerance to bending (flexible); however, toughness of such structures is naturally lower.
- Nongraded porous nanocomposites exhibit higher fracture load.
- Flexural strength and modulus are highly dependent on the direction of the exerted load.
  - Spherical nanoparticles offer higher flexural strength.
  - Nanorods offer higher flexural modulus to the structure.

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