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Reinforce Fabricated Nano-Composite Matrixes for Modernization of S & T in New Millennium

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Abstract

Rational fabrication of futuristic smart materials like polymer-derived nanocomposites/matrixes is ever desirable due to innate worth in advancement and growth of S&T. Certain nanocomposites are designed from metal-polymeric blends through altering varied parameters like shear stress, shape, size, rate, concentration and processing time, which are best used as fillers. Reinforced fabricated polymer nanocomposites possess exclusive physicochemical characteristics like non-Newtonian/constant viscosity-free stress, time-dependent mechanics, facile shear-skeletal revisions and viscoplastic course controls. Metal-derived nanocomposites/matrixes showed substantial inherent rheology being vulnerable for designing viable applicability in photovoltaics, catalysis, optics, drug delivery, smart material and energy storage. Bottom-up technique is used for self- and directed-assembly of polymer-based building blocks owing to robust fabricated and efficiently manipulated/targeted reinforced 1D, 2D or 3D nanostructures. This chapter reviews some contemporary advances in reconfiguration of rational designing of certain polymeric nanostructures/composites with current and futuristic developments. This overview highlights significance of assured reinforced matrixes in S&T besides disclosed fundamental principles involved in material designing/engineering of multifaceted nanomaterials. Assorted advanced developments are made to avail futuristic prospective of biopolymers, viz. chitin, chitosan, cellulose and lignin in order to offer unequivocally myriad applications in modernization of science and technology in new millennium.

Keywords: biopolymer, composite, chitosan, cellulose, nanocarbon, matrix, dendrimer

1. Introduction

The Latin term *nannus* meaning dwarfness is in fact adopted for the prefix *nano* [1]. Nanotechnology deals/controls the matter at both atomic and molecular developments, creating and modifying structural components in all possible dimension levels (1D, 2D, 3D etc.). Nanoparticles/nanomaterials showed extraordinary features due to inbuilt molecular/atom-by-atom accuracy that is deficient in conventional bulk counterparts/materials [2]. Nanotechnology manipulates structures/skeletons of matter at atom/molecular scale. “Nanotechnology” was coined by Norio Taniguchi in 1974, and in 1959, Richard Feynman gave the famous

quote “There is Plenty of Room/space at the Bottom,” which is trusted in assorted making of nano-scale machines. IBM Zurich researchers in 1980 invented tunneling microscope for material analysis at atomic/molecular dimension [1, 2]. Nano-composite matrix holds particles in one or more filler layers/sheets with superior surface:volume ratio at a magnitude of few nm units. Nano-dimensional alterations are found to reduce material size and shape without changing its native features and besides fairly reward novel features including alter elasticity, robust mechanical power, tunable heat and electric conductance or insulation, and impart particular reactivity that are absent in corresponding micro-/macro-scale dimensions. The interfacial-phase interactions that exist at nano-dimension scales are superior due to augmented intrinsic characteristics of the material, as multiphase combinations of constituents in fabricating nano-composite matrixes impart certain innovative qualities that are quite superior to residual participating constituents.

Assured nanostructures/skeletal matrixes derived via reconfiguration/reinforcement establish a myriad of functional importance in advancement of today’s science and technology [2, 3]. Nanotechnology executes superior technological reconfigurations through strategic maneuvering of matter at an atom, molecule or supramolecular dimension at a magnitude less than 100 nm [1–3]. Reinforcement of atomic/molecular frameworks and material manipulation are performed at nanometer (10^{-9} m) scale via nanotechnology, which exactly manufactures micro-, meso- and macromaterials under its vast domain. In general, nanostructure matrixes exist in the form of amorphous, crystalline and polycrystalline states that embed variable size/shape including metallic, ceramics and polymers, besides offering single or multi-phase chemical compositions and designed orientations [2]. Nowadays, all such reinforced and reconfigured nanomatrixes own innate distinguishing scientific edicts in scientific and technological modernizations. The defensive features of meso-/micromaterial get enhanced at the nanoscale due to alteration of limiting features via augmenting physicochemical, biological, mechanical, electrical and electronic parameters. Reinforced/reconfigured nanomaterials own specially intended characteristics, viz. huge surface area, no/less surface defects and high surface/mass ratio that are best exploited in nearly all S&T achievements [4, 5].

Today, nanotechnology is expanded with a novel horizon, yet R&D in materials science is in a much infantile phase, though nanoscience capably upgraded standards of every domain including energy production/storage, information technology, pharmaceuticals, metamaterial, nanomaterial, food, biotechnology and wastewater/water, biomedical, environment and instrument/device [1–4, 6]. Advance re-configured designing yields diverse matrixes that are used in myriad applications like coatings, sunscreens, cosmetics, textiles, paints, cutting boards, socks, diodes, pacemaker, scaffold for hip/bone/ear joints and electrodes for H₂O splitting. Amid nanomaterials are nanocarbon, nanosilica and identified nanometals like copper, silver and gold, besides awarded nanometal oxides of iron, cerium, nickel, aluminum, titanium, zinc etc. along with a unique entity called quantum dots [3, 4, 6, 7]. All such fabricated composites/hybrids/matrixes being ubiquitous are tailored for endowing best vigor, stiffness and design practices, which have been trusted throughout the modernization of S&T.

2. Reinforced and designed composites/matrixes

Rationally designed/reinforced composites own specific strength and modulus over analogous materials like metallic alloys, steel and other metallic compositions [4, 6, 7]. Certain nonfiber matrixes are reinforced owing to varied highly anisotropic structural features that differ from isotropic polymers, metals and ceramics.

All such rationally fabricated reconfigured matrixes display extraordinary features like environment sturdiness, damage tolerance, non-erosive, sturdy thermo-oxidation, non-flammable and attenuated electric or heat conductance besides offering especial utility in proactive surface designing and possessing integrated networking. Such reinforced matrixes/composites offer many applications like water purifications, supercapacitors and green energy/power creation and anti-corrosive, antistatic, antiballistic and electroconductive devices.

The twenty-first century seeks special/smart materials with properties subjective to the remarkable varying conditions of their functioning. Such smart materials are reconfigured via advanced nanoscience innovations due for stunning and unique designing opportunities for advancement of science. Reinforced composites/matrixes have eventually modernized S&T via a myriad of applications including optoelectronics, biosensors, photodetectors, photocells, nanomaterials and plasmonics [1–4, 6–9]. Nanocomposite/matrix offers environmental-friendly prospective for all sectors including chemistry-, physics-, bioscience-, engineering and technology-based industries and businesses. Nanomaterials have explored, inspired and motivated interdisciplinary R&D and accordingly trusted scientific growth. Nanosize designing improved physicochemical properties of materials through exceptionally determined functionalities and paved new trends besides modern developments. Today, R&D comprehensive findings conferred assorted innovative nanocomposites of assorted materials including chitosan, cellulose, metals, polymers, clays, carbon and graphene owing to numerous applications [10]. Nano-technologically developed material matrixes behold systematic captivity at nano-scale due to smartly carried advanced reconfigurations or reinforcements in their skeletons. Reinforced polymeric matrix own rigid dispersed phase owing constituted particles with nanodimensions exists with long range flexible-rough linkages. Nanopolymer networks that are amorphous/semicrystalline own reasonably stacked and intercalated inter-phase morphology. Entropic morphological alterations are viable due to interactive component configuration [3].

Reconfigured composite contains incessant fortified pattern owing to reinforced physicochemical features that yield through two/more discrete constituting phases of mainly fibers, whiskers and metamaterials, polymers, metals and ceramics [1–4, 6–10]. In 1960, Richards Feynman's research in field of quantum computations really fascinated the entire scientific community toward nanotechnology; besides aiding to develop several material-based blends/composites/matrixes in order to furnish extensive applicability at that time, they still continued to explore various advanced nanostructures to be used in modernization of today's S&T. Sophisticated unique characters get inculcated in nanocomposites/matrixes imparting high modulus, specific strength, tailored performance, boosted resistivity in fatigue and corrosion besides embryonic reconfigured processing. Nanotechnology reinforcements can let mass diminution that is missing in usual counterstructures and contemporary materials, thus creating good substitutes. Supplementary complex functioning can be significantly enhanced by means of reinforcements that are unattainable in normal materials. Innovative structural strengthening can be attained via anisotropic or isotropic alterations at all altered phases in the constituted/reconfigured frameworks. These reinforced composites /matrixes offer special infrastructure developments in material designing and engineering like bridges, pipelines, transportation materials, automobiles, cermets, aircrafts and ships [3, 4, 6, 7].

3. Nanocarbon intercalated polymeric matrix

Assorted material components easily enter polymeric/biomolecule skeleton in synergistic pattern yielding nanobiocomposites and imparting advance structural

features as an alternative to classic synthetic/natural polymers. Consequently, various inorganic materials including metal particles, carbon nanotubes, ceramics and clays are blended in biopolymers resulting in a diverse nanocomposite/hybrid like polymer-inorganic, metal-polymer, metal-ceramic and inorganic-organic phases [10]. All these rationally designed/reconfigured nanocomposites/hybrids/matrixes endow many applications, viz. biosensor, marker, biochip, optic, electric, electronic, photoconductors, biocompatible tissue engineered scaffolds/templates and drug release/filter. Monomeric inorganic/organic hosts/frameworks can be reinforced with many natural/bio- and synthetic polymers resulting in intercalated polymer networking composites [11]. Such matrixes are obtained via assorted techniques, viz. microwave, colloid interaction, suspended polymerization, solvent evaporation, electro-spinning, spray-drying, porous glass membrane spraying and emulsification. So, superior techniques are used for the development of desired characteristics like not expensive, competent, control/tunable shapes/sizes, porosity, density and surface area in reconfigured matrixes as devoid in counterparts.

Rationally reinforced polymeric nanocomposites hold host-guest intercalated morphological permutations and combinations of inorganic/organic frameworks like nanocarbon, metal, clay, montmorillonite, ceramic, poly-vinyl alcohol/chloride and zeolite [12]. Template or chosen material that holds native stupendous physicochemical characters is too vulnerable in the derived matrix. Reinforced composites/matrixes offer distinctive significance in electric, electronic gadgets, tissue engineering, packaging, coatings, biomedical, nanodevice feedstock, photosensitivity, catalysts and antimicrobials and disinfectants besides physico-chemical analysis. Various technologically reinforced 1D, 2D and 3D composites/matrixes own boosted intrinsic features and corresponding applicability domain as shown in **Figure 1**.

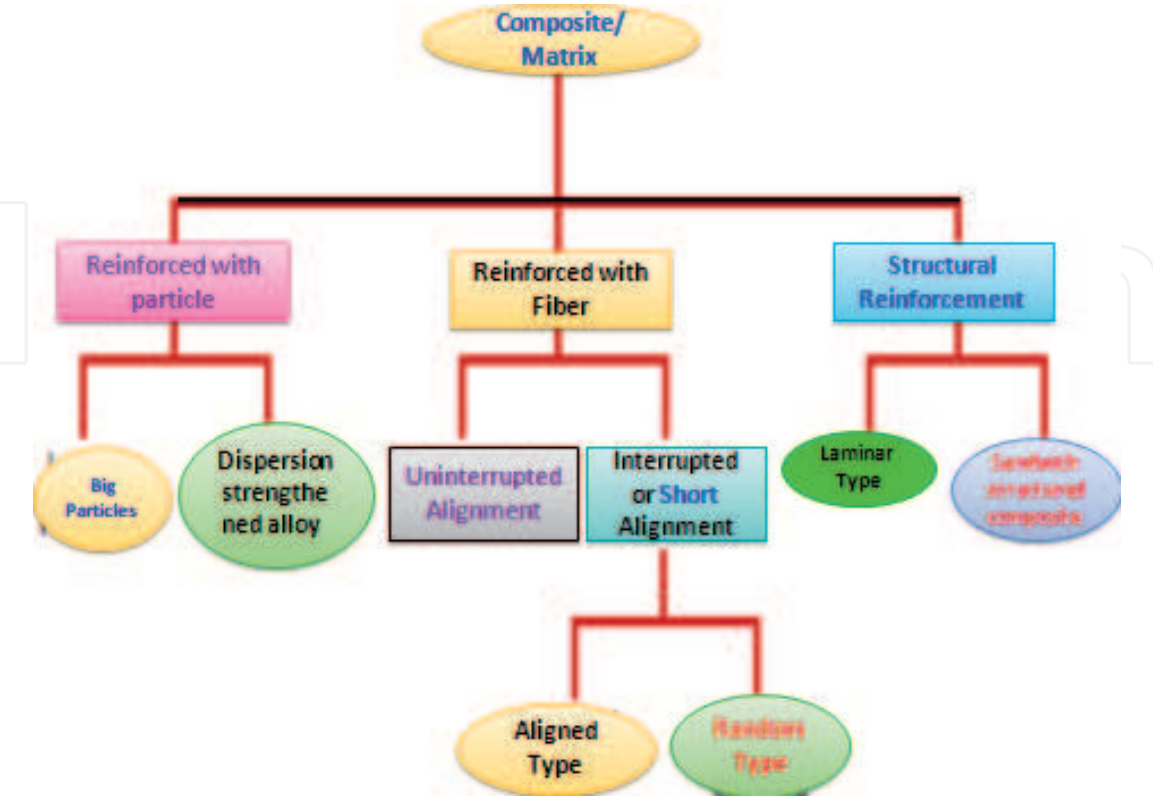


Figure 1.
Technologically reinforced various composite matrixes [1, 2].

4. New millennium advanced material matrixes in S&T

Today, smart materials have manifested assorted benefits and it is hard to envisage the modernized advancements without their contributions. Advanced materials endow a myriad of applicability in industries like chemical, mines, metallurgy, oil-gas extraction, refinery, power, and modern technology, viz. aerospace, IT, communication construction, transportation and genetic engineering. Smartly designed/reconfigured matrixes have to face few technically notable challenging domains being adept at power turbines and well robust aerojet engines etc. Certain smartly designed super-alloys are found to fulfill numerous such methodological challenges and demands that own practically efficient utilities in an industry besides R&D. Accordingly emerges prototype thrust in R&D of material and prevalent advanced nanotechnology assisted rational fabrications of smartly functional matrixes thus continued Richards Feynman initiated timeline advancement of nano-materials. Today, paradigm nano-technological developments have stimulated rational reconfiguration of materials and ultimately pave a path for designing classic, competing and preferred matrixes or composites for strengthening S&T in the new millennium.

This twenty-first century, invoke technological advancement in smartly designing and rational reconfigurations of nano-material matrixes to be developed via amalgamating incredible features of constituents in resultant composites (as meso/micro-porous materials like alloys, blends, ceramics, natural and synthetic polymers found to miss such designed features. More smart materials like 1D, 2D or 3D have to be architected via reinforcement of two/more phases in vigor and firmly intercalated material framework as achieved in material engineering for sturdy, reinforced and robust output [3, 4, 6–12]. Augmented and perceived performance is practicable in such composites by means of particulate segregation due to tailoring of raw-skeletal elements. Advanced and sophisticated techniques aid in designing and reconfiguring assorted materials including natural and artificial origin. These reconfigured composites/matrixes are beneficial due to lesser density, superior directional mechanics, precisely enhanced tensile strength than steel/metals, elevated fatigue survival, adaptable tailoring/designing, facile machining and cost-effective synthesis. Directional arrangements of constituting matrix mutually control mechanical strength and functional properties of resultant composites. Parallel longitudinal atomic/molecular arrangements are obtained via solitary pathway and fully random configurations that are generally allied in the following sense: (a) Owing to irregular associations (b) Easy arbitrary/partial adjustments (c) Very much strengthening resultant composites due to small diameter, less surface flaws and facile suppleness over bulk materials (as seen in glass, aramid/kevlar and carbon fiber). Assorted 1D, 2D or 3D reconfigured material matrixes/composites are discussed in the following sections:

4.1 Fibrous composites

Certain fibers owing to greater length than diameter and (l/d) ratio imparting valuable shear pressure reassign reinforcement in arbitrary direction in their skeletons resulting in the most persuade fibrous composites as shown in **Figure 2**.

4.2 Carbon-reinforced composites

Carbon-reinforced composites have high reinforcement in their polymer matrix due to their innate tensile modulus and elevated strength at eminent temperatures, which are unaffected by water or other solvents, acids and bases. Carbon-reinforced composites display a variety of physicochemical and mechanical characters as

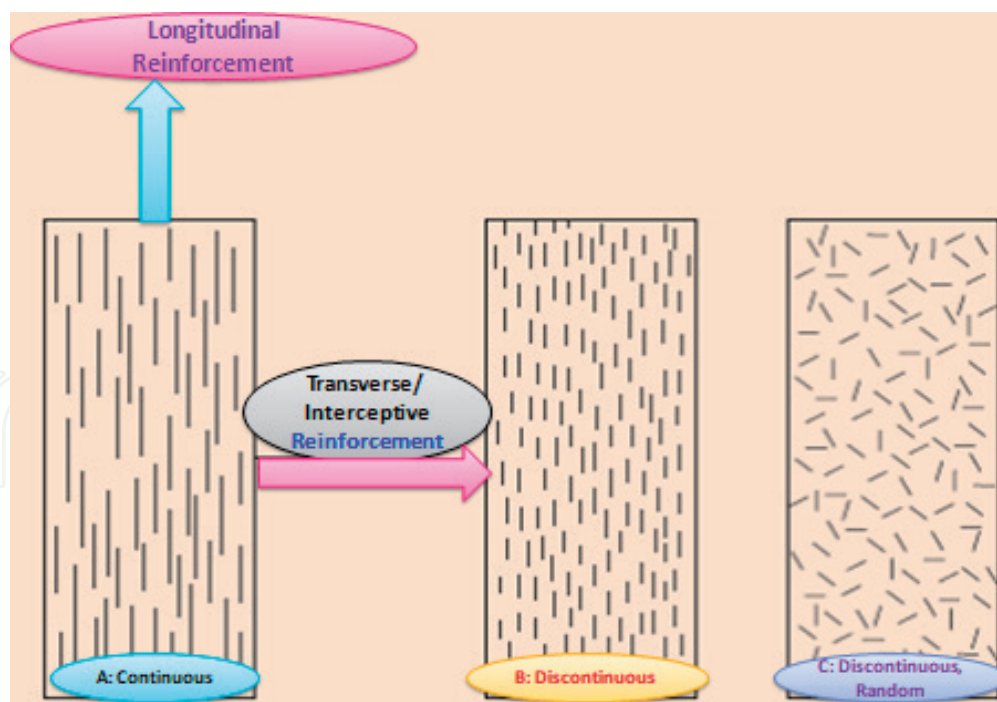


Figure 2.
Assorted orientations in fibrous reinforced composites [1, 2, 13].

exploited to get specific/rationally designed products like thermoplastic at quite a cheap cost. Such carbon-reinforced composites have huge strength:weight ratio and rigidity as needed in aerospace, transportation superstructures, automotive, engineered products, scaffolds and smart equipment. Certain fiber-reinforced plastic/composites are fabricated through polymeric matrix like organic/inorganic fibers, paper, wood and asbestos, which caters to the needs of aerospace, automotive, marine and constructions besides ballistic armor. American Chemist Leo Hendrik Baekeland in 1905 had replaced shellac-resin (yield from lac bug's excretion) with synthetic Bakelite polymer obtained via phenol-formaldehyde reaction at controlled pressure and temperature, and it was the world's first synthetic plastic that was fiber-reinforced [14]. In 1936, du-Pont obtained resin-composite through "fiber-glass" blending with plastic followed by modern *cyanamids* resin in 1942. Glass, carbon and aramid fibers are still used in making fiber-reinforced plastic/composites. Certain polymer-reinforced combinations are stated in **Table 1**.

4.3 Metal matrix composites

Metal-based matrixes/composites are obtained through ductile metal particulate fortification via continuous and discontinuous or whisker fiber molds. Reinforced composites appear as green/benign materials owing to special features like precise rigidity, nonflammability, high stability, abrasion/creep resistance and thermal/electrical conductivity besides sustainability at serviceable temperature and pressure than their counterparts [15]. But metal matrix composites are much more expensive than other reinforced composites, so they possess limited utility. Superalloys and alloys of metals are engaged in making such metal-based matrixes/composites [15, 16]. Continuous fiber moldings utilize assorted organic and inorganic fibers like carbon, silicon carbide, boron, aluminum oxide and certain refractory metals, while discontinuous path of reinforcements involves fibers of silicon carbide, aluminum oxide, silicon oxide and carbon [17]. Metal matrix composite yield via dispersion of reinforced fabric in metallic template and reinforced surfaces gets coating to avoid auto-oxidation. The template is made

Reinforced matrix/ composite	Constituting components	Superior features
Glass-based fiber	Epoxide, polyamide, polycarbonate, polyoxymethylene, polypropylene, vinyl ester, polybutylene terephthalate	Strengthen expansion coefficient, own great electric and heat resistance
Wood-based fiber	Polyethylene, polylactic acid, polypropylene, acrylonitrile butadiene styrene, high-density polyethylene	Flexural potency, high tensile modulus and strength
Carbon- and aramid-based fiber	polyepoxide, polyester, vinyl ester, polyacrylate	Suppleness, high tensile strength and solidity, electrical strengthen
Inorganic materials	Semicrystalline thermoplastics, UP	Isotropic contraction, graze, high solidity potential strength
Chitosan	Metals, nonmetals, synthetic and natural polymers	Flexible strength, alternative surface characters
Microsphere	Glass micro-/mesospheres	Less weight, solid fillers

Table 1.
Various reinforced composites with superior applicable features [13].

up of monolithic material wherein the reinforced fiber gets embedded through continuous moldings. Highly structured metal matrix/composite is derived through aluminum, magnesium or titanium metallic supports for reinforcement with fibers. The reinforced fiber can be embedded into metallic skeletons achieving either constant or irregular structural tasking, which can modify certain physico-chemical features, viz. wear/shear resistance, friction coefficient, and thermal and electrical conductivity [18].

Metal composite is reinforced through continuous or discontinuous mode of fabrications, viz. extrusion, forging and rolling so as to get isotropic matrix besides usual polycrystalline diamond tooling. Continuous reinforced technique embeds monofilament wire/fiber of boron, carbon and silicon carbide in assured path and yields anisotropic arrayed metal composite, while discontinuous reinforced technique uses fuzzy short fiber/particles of alumina and silicon carbide. The high temperature treatments are needed in fabrication of metal involved matrixes developments in order to obtain the best dispersion of constituting fiber skeletal interfaces (as on cooling yields residual strain amongst metal and reinforced fibers being vital for best composite formations [4–6]). This controlling residual stresses notably manipulates mechanical instincts of fabricated metal composites. Many metal matrix/composite have two constituents: one as metal and the other may/may not be metal or may be ceramic and/or organics. If three or more metals are used, the resultant matrix is termed as hybrid. Such metal-based matrixes/composites are complementary to heat-resistant materials like ceramic and sintered metal. Hybrid composites are innovative fiber-reinforced matrix acquired through mixing of two/more fibers imparting improved features than other composites. Reinforcement of polymeric resin with pretty firm and low-density materials like carbon and glass fibers yields sturdy/tougher composites besides superior resistive plastic hybrid composites [15]. Certain hybrids/composites found to possess aligned and thoroughly amalgamated fiber layer besides mutually alternated depositions impart anisotropic properties owing to finally harmonize template phases. Some hybrid composites are foremost in their typical applicability in constructing lightweight structural units, orthopedic components, sturdy transporting templates used in aerospace, marine

goods, sport items and trivial stuff infrastructures in building constructions [15–18]. Lightweight military aircrafts and helicopters are made with such rationally designed hybrid composites offering 20–40% reduced weights than contemporary materials. Glass fiber-reinforced carbon fiber yields hybrids/composites to be used to make rotor blades of helicopters due to innate superior fatigue resistivity as needed in making futuristic hypersonic fighter planes and aircrafts [1, 19].

4.4 Structural composites

Structural composites are obtained through geometrically designed structural elements in homogeneous pattern derived through constituents. Laminar and sandwich plates come under the category of structural composites. The strength properties of advanced structural composites offer broad mechanical properties as controlled by many parameters like volume/weight proportions of reinforced fiber/matrix components, built-up formulations, constituent mechanical features and orientations via uni- or bidirectional, besides various off-axis directional/random, arrangement. Sandwich panels are designed as lightweight structural composites owing to their comparatively elevated mechanical strengths. Such sandwich configured composites are very unique as fabricated via attachment of two thin and rigid skins to yield lightweight but bulky core slotted panel own dual outer face of relatively stiff and strong template like metal alloy, fiber-reinforced plastics, steel, and plywood adhesively bonds to thicker light-mass inner hub materials. Sandwich panels consist of inner core material made up of lightweight and low elasticity modulus like polymeric skeleton phenolics, epoxy, polyurethanes, wood and honeycombs [15, 20], while outer sheets in sandwich panels consist of tough/rigid materials so as to communicate high mechanical strength under high tensile/compressive strain loading. Sandwich panels-based structural composites offer wide utilities including in buildings' roofs, floors and walls, besides being used in fabrication of wings, fuselage and tail plane skins of aerospace and aircrafts [21–23].

4.5 Laminar composites

Some laminar composites yield through single layer fiber laminated mutual bonding or stacking own accordingly paved orientations of latent directional fluctuations achieved via consecutive depositions. The particulate platelet or laminar matrixes possess two long dimensions, e.g., wooden thin layer plywood with consecutive layers that are quite isotropic composites due to dissimilar grain/fiber orientations that are weaker in any direction than it would be if constituting fibers could all be aligned in one direction [1]. Layers of assorted fiber reinforcement yield hybrid laminate revealing anisotropic and directional structures. Based on stacking order of each layers, laminated composites owing to their in-plane and out-plane bend-stretch coupling ultimately give in-plane loading. In fact, laminar composite has two-dimensional panels or sheets with favored directions to attain highest strength [6–8]. Wood and plywood material is basically a laminated composite holding constant reinforced and preferred directional stack layer of fiber orientation instead of adhesive joints. Such laminated composite layering fetches each grain at 90° angle with its neighbors. Laminated composite attains superior mechanical strength, stability and appearance as assembled via heat, pressure and adhesive treatments. Assorted laminated composites are obtained, depending on constituents and the processing applied in their manufacturing [1–4, 6–12, 14, 15, 24]. Certain plastic-laminated glassy-type composites behold tight fit adhesiveness at their solid countertop surfaces, which were found to protect the particleboard. Cellulosic templates appear good substrates for assorted matrixes as obtained

through overlay thermo-processing, e.g., laminated composite panels, medium density fiber-boards, decorative foils, high-pressure decorative composites, wood/multi-laminar veneer and resin-saturated decorative papers. Recently, numerous layer-wise dimensionally organized products like special glue/laminated timber composites are developed owing to mutual lumber bonding viable for durability, water-resistance and structural adhesiveness in resultant products, e.g., glulam a versatile stress-engineered wood beam composed of special laminations [1].

4.6 Lignocellulosic composites

Environmental causes urge to develop green composites based on renewable sources like biopolymers as economic options for glass/carbon fiber-derived composites [25]. Thus, plant-, jute- and sugar cane-based lignocellulosic composite-derived matrixes can serve this purpose. Fabrication of organic-based nanocomposites arose as a multidisciplinary area in advanced nanotechnology, particularly procured through sustainable and eco-friendly resources and methods. Some green composites are also obtained via reframing natural/bio-polymeric framework via amalgamating other natural/synthetic material substrates that offer morphological/interfacial design characteristics in resultant products over conventional counterparts [26]. Assorted biopolymeric skeletons, viz. starch, alginate, dextran, carrageenan, chitosan and cellulose, are formulated/envisaged due to their innate functional features like nontoxicity, biodegradability and biocompatibility [2, 3]. Natural lignocellulosic fibers have semicrystalline cellulose microfibril orientation offering multifunctional nanotechnological fabrications so as to cater to advanced applications in S&T as mentioned below:

4.7 Cellulose-derived nanometal matrixes

Cellulose is an extensively copious natural polymer and component of the “plant’s skeleton” that exists on Mother Earth [1]. In fact, cellulose shares the same chemistry and molecular structures but imperative morphology and mechanical variations based on its recovery from various sources like vegetable, plants and bacteria. Nanocomposite matrixes are derived through cellulose skeleton via amalgamation with different phases of organic and inorganic materials [1, 13]. Nanofibrillated and bacteria-derived cellulose is made up of nanodimensional fibers, which impart novel and improved native qualities in resultant nanocomposites than vegetable-derived cellulose [13, 27]. Cellulose has soft matrix to accommodate inorganic/organic materials via blending diverse fillers to yield composites owing to their inherent functionality of constituents besides transporting unique functions due to biointerfacial alteration [7, 27]. Various material like nano-metals including gold silver and copper and inorganic gets easily doped/filled in the cellulose skeleton and yield composites which own altered fibers interaction at surfaces over bulk analogues besides coalition of fillers is beneficial for improvement of opto-electronic/electrical and mechanical functions [1, 2]. Cellulose has an exclusive arrangement and discrete affinity to form intra-/intermolecular bonding, which compacts its supramolecular ester/acetate and ether as dynamic derivatives utilized in coating, pharmaceuticals, food and cosmetic industries [12, 27]. Hybrids of cellulose procured through nanometal/metal-oxides yield assorted nanocomposites like *Nowa-74* used as calorie-free dessert in food and wound dressing scaffolds in biomedical and optoelectronics. Water filtering nanomembranes are reinforced through 3D cellulose matrix owing to its brilliant characters like high purity, high polymerization degree, elevated crystallinity, high elasticity and mechanical stability and huge surface area. Certain physicochemical

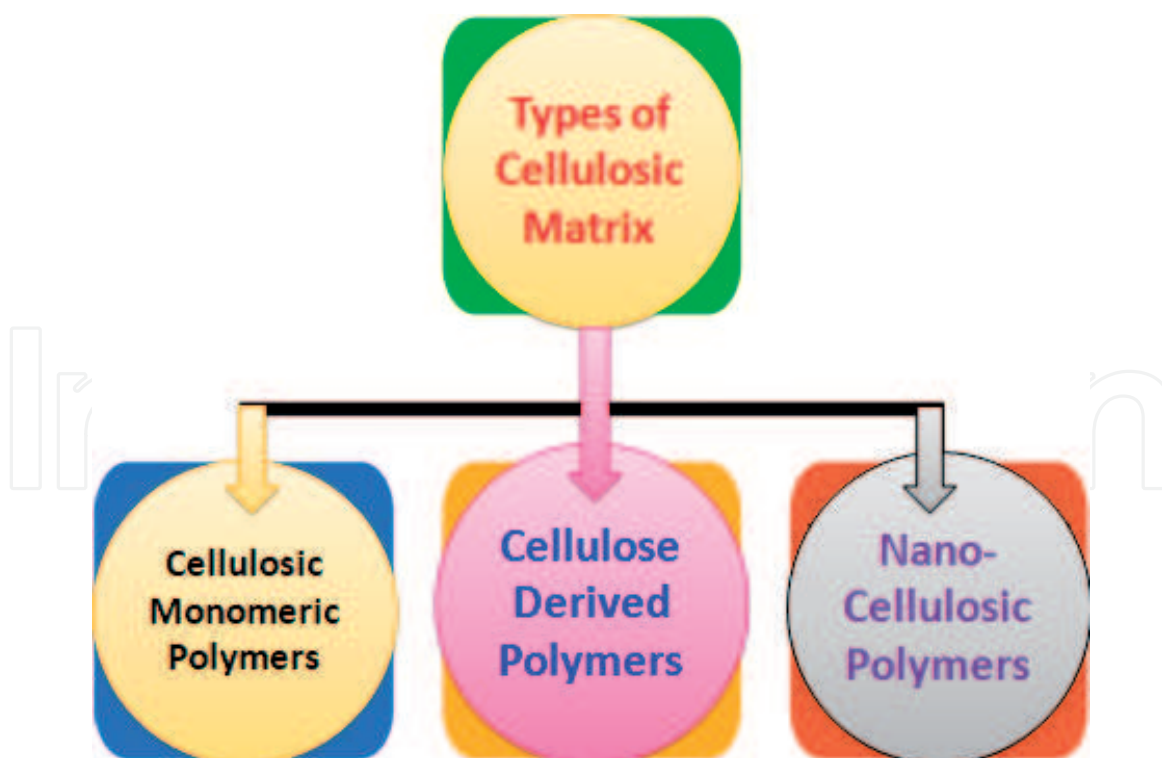


Figure 3.
Types of cellulosic matrix [1, 2, 27].

adaptations are facile to reinforce in nanofibrillated cellulose matrix so as to yield multipurpose paint additives and lacquer/latex. Reconfigured cellulose composites are obtained through inorganic nanoparticles/metal aggregates and/or other polymer blending via techniques of homogenized aggregation and in-situ metal-salt reduction in suspensions. Macromolecular networkings of cellulose matrix can be developed via facile templates and ensue nanometal distributions into its skeleton without further aggregations [13, 26–28]. Carbon reconfigured nanocomposite has received much attention due to reinforcement in mechanical features besides boosted electrical conductivity, which is additive for automotive fuel stroke components entailing electric conductance. The types of various cellulosic matrixes are depicted in **Figure 3**.

Cellulose attracted considerable attention as the strongest potential feedstock for bio-based polymer productions [1, 27]. Thus, noteworthy reinforcements in different cellulosic matrixes are done to get assorted nanocomposites. Cellulosic derivatives act as prominent filler/matrix in getting resourceful biosustainable options to high-quality synthetic polymeric composites besides substituting most petroleum-derived functional counterparts. Eco-sustainable cellulosic-reinforced nanostructures offer prospective functions with a wide applicability from energy-storage devices to biomedical scaffolds [1, 2, 13]. Cellulose is the most plentiful natural polymer and component of cell walls of plants and is also found in diverse genus, viz. algae, fungi, bacteria and sea animal/tunicate. Cellulose substance contains linearly placed and alternate stereo-configured units of D-anhydro-glucopyranose homo-polymeric bonding with 1, 4- β -glycosidic aggregations that exist as micro-fibrils [1, 2]. Morphological variations in cellulose control the degree of polymerization, which varies as per its resources. Huge hydroxyl groups on the glycosidic chain of cellulose via hydrogen bonding upshots manifold cellulosic microfibrils owing to elevated mechanical strength, rigidity, stability and biocompatibility. Hydroxyl functionality of cellulose skeleton is facile to undergo assorted physicochemical reinforcement like etherification, carboxy-methylation, cyanoethylation and hydroxyl-propylation yielding assorted derivatives for viable

Cellulosic composite	Cellulose functions	Cellulose-reinforced composite property
Cellulose-lyocell/acetate, butyrate composites	Matrix/ filler	Increases tensile strength, dimensional stability, matrix compatibility, biodegradability.
Cellulose-lyocell fiber/PLA	Filler	Unexpectedly high biodegradability, significantly high mechanical characteristics.
Ethylated-cellulose, hydroxypropylated-cellulose, polyacrylated-cellulose and calcium phosphated-cellulose composites	Filler	Increases thermal and mechanical performance.
Cellulose fiber/polystyrene composites	Filler	Increases flexural storage modulus and processing speed.
Cellulose fiber/high-density polyethylene composites	Filler	Improves thermal and mechanical properties.
Cellulose particles/chitosan composite film	Filler	Enhances mechanical properties and adsorption capacity of chitosan film.
Regenerated cellulose film/BiOBr composite	Matrix	Cellulosic film own cavity for BiOBr particles and expanded specific surface area via porosity feasible for efficient photocatalysis.
Cellulose/MMT clay composite films	Matrix	High-strength cellulose composite films with excellent antibacterial activities.
Cellulose film/graphene oxide composite	Matrix	Superior mechanical performances and excellent ultraviolet-shielding properties.
Cellulose acetate/hydroxyapatite mineral composites	Matrix	Reinforced matrix holds tough HaP-cellulosic interactive ductility use to remediate pollutant.
Carboxymethyl cellulose/carbon composites	Matrix	Reinforced cellulosic composites own huge potential as sensors in bioelectronics.
Cellulose paper/carbon nanotube film/composite	Matrix	Reinforced composites are flexible, tough, thermally stable and own uniform electrical conductivity suitable for advanced biotech use.
Methylcellulose/keratin hydrolysate membranes	Matrix	Protein and polysaccharide reinforcement improves mechanical and thermal properties.
Cellulose fibers/iodine composite	Matrix	Cellulosic composites enhance photo-induced conductivity.
Cellulose acetate-polyaniline-derived membrane	Matrix	Cellulosic membranes enhance conductivity mechanical biocompatibility.
Polyhydroxybutyrate/ethyl-cellulosic-derived films	Filler	Polyhydroxybutyrate/ethyl-cellulosic reinforced formulation reduces crystallinity, promotes degradation and boosts physicochemical characters viable for sustainable biocompatibility anticipated in biomedical and coatings.

Cellulosic composite	Cellulose functions	Cellulose-reinforced composite property
Polyhydroxybutyrate/polyhydroxyalkanoate-cellulosic composites	Filler	Cellulosic reinforcement boosts physical-mechanical strength as suitable for packaging.

Table 2.
Assorted cellulosic formulations as filler for making composites [1, 2, 13].

nanocomposites. Specific chemical formulations like ester-acetate and ether-methyl/carboxy-methylation in cellulosic hydroxyl functionality are augmented characteristics aiding in rational reconfiguration of advanced nanostructures, so it is preferred over cellulose feedstock [18, 21–23].

Visco-processing of cellulose matrix is done through derivative formation and without de-polymerization, which yields valuable products like cellophane and nitrocellulose. This cellophane acts as transparent sheet for low permeation purpose, and nitrocellulose is an excellent feedstock forming basis for rayon: the first “artificial silk” since many decades. Cellulosic derivatives were used as good feedstock for making thermoplastics since the beginning of nineteenth century. Cellulosic-reinforced formulations like cellulose acetate and cellulose esters are facile to mold as extrusion and films, besides being used in making construction materials, paints, pharmaceutical scaffolds and biodegradable plastics [1]. Cellulose-derived polymeric composites are obtained through integrating nanocellulose into assorted synthetic/natural polymeric matrixes as current advanced materials owing to their extensive applicability. Since the 1980s to the present, R&D led several innovative cellulosic reinforcements, which perk up glycol-polymeric insertion so as to yield superior functional biocomposite-derived cellulose [28]. Assorted cellulosic formulations obtained through reinforcement in host matrixes are mentioned in **Table 2**.

4.8 Advances in reinforced cellulosic nanomaterials

Currently, cellulose biopolymer can be integrated into two types of polymer nanocomposites: nanocellulose-based nanopolymer composites and nanocellulose platform-based nanocomposites. Viable applications of reconfigured cellulosic nanocomposites are shown in **Figure 4**:

Advanced biotechnology utilizes assorted biopolymer cellulosic forms including natural fibers, nanocellulose and cellulose derivatives to undergo characteristic diversified and sustainable functional variations to yield alternative composites for multifunctional usages. Copious cellulose acts as foremost natural feedstock option for fossil resources in fabricating reinforced martial matrixes [1]. Polylactic acid reinforced in cellulose matrix offers biodegradable, exceptionally sturdy and non-toxic nanocomposites called cellulosic bioplastics with superior thermal, electrical and mechanical features. Cellulosic bioplastics and functionalized nanocrystals are benign, inexpensive and robust serviceable composite owing to their well-reinforced structures of constituting matrixes for deriving electrochemical and energy-storage tools. Poly-hydroxy-alkanoate integrated/filled cellulosic matrixes yield eco-friendly composites as a substitute to synthetic polymers for food packaging, plastics and biomedical templates [1, 2]. Cellulose-reinforced composites cater to today’s challenges via development of sustainable and green products through economic, environmental and social perspectives, though cellulosic biopolymeric composites fulfill partial confronts, which are to be tackled in futuristic R&D. Fully compatible two-phase polymeric composites need to be developed through materials science and process engineering in cellulose chemistry [26].

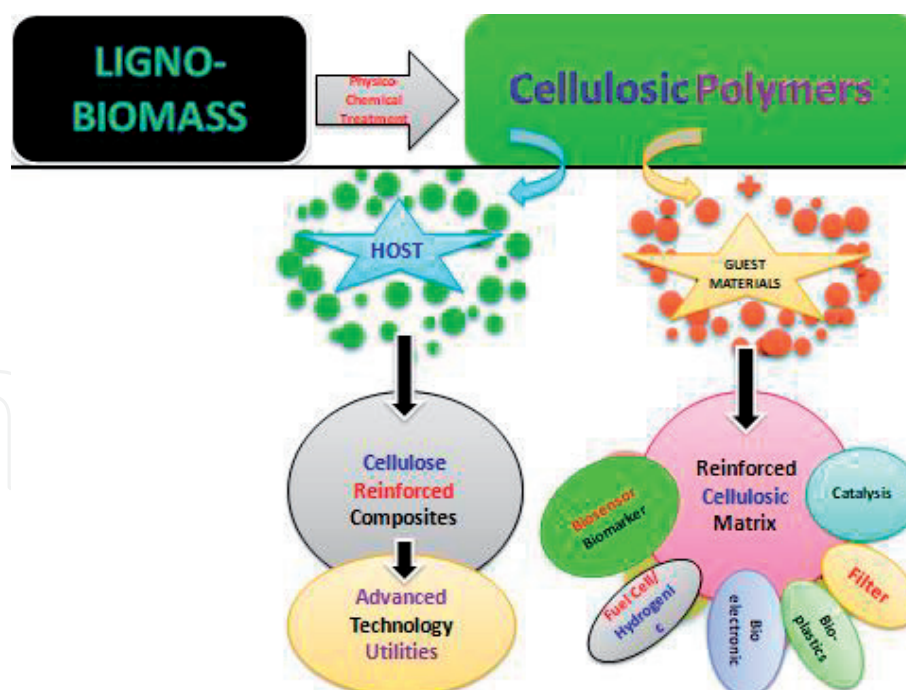


Figure 4.
 Viable applications of reconfigured cellulosic nanocomposites [1, 2].

4.9 Cellulose nanocomposites

Cellulose is the copious bioproduct through plants, animals, bacteria and flora-fauna. Its extensive linear chain polymer is composed of 1,4- β -linked D-glucopyranose assembly in the hierarchy of microfibrils with excellent strength and stiffness. Nanoscale/dimensional cellulosic matrixes are reconfigured in assorted forms like nanocrystal, nanofibers or flakes. Nanocellulose matrixes appear safe, versatile, biodegradable and biocompatible without any side effects on health and environment. Reconfigured cellulose matrixes own small thermal expansion coefficient, huge aspect ratio, and superior mechanical, optical and tensile strength features. Thus, they are preferred for special utility including thermo-reversibly tenable hydrogel, paper making, coating, additives, food/drug packaging, lithe screens/films and lightweight ballistic protection beside usages in automobile windows. Assorted cellulosic composites are reconfigured, viz. dispersed phase nanofillers, dispersed phase matrix, and interfacial region hybrids owing to their potential biomedical significance, namely targeted drug/gene/cell delivery/carrying and fabricating temporary implants with PHB sutures besides making stents. Cellulose skeleton is fragile to reinforce with diverse nanometals via innate hydrogen bonding so as to yield supramolecular nanoclusters as best utilized in textiles due to native antimicrobial, antibacterial and improved catalytic parameters [26]. Nano-cellulosic reinforced polymeric matrixes owe undo recombined dynamic covalent mechanophoric linking which imparts self-healing capacity due to surface modification via scissile chemical bonding [1]. The reinforcement of material phases and skeletal faces is found to boost its surface activity in the ensuing matrixes, and due to self-supported healing, it further gifts superior sensitivity to mechanical stress transports [2]. Typical nano-cellulose composites have compacted lingo-cellulosic biomass and alter its innate characteristics like fibrils have crystalline features and high strength and mechanical rigidity. Certain nano-cellulose-based matrixes have especial features like light-weight, highly dense (1.6 g/cc) and lofty tensile strength (10 GPa at par with cast iron), e.g., nano-cellulosic matrix with proactive hydroxyl functionality provides designed and desired applications in S&T [28].

4.10 Dendrimer-reinforced polymeric matrix

Dendrimer architectures via click chemistry and self-assembly have put forward major reinforced polymeric matrixes. Advanced nanotechnology has discovered new nanoperiodic system through dendrimeric reinforcements in the form of nanodevices, nanomaterials and nanomedicines. This decade has developed many scientific and commercial utilities focusing architecturally on drive characteristics through assorted dendrimeric reinforcements. Dendrimeric reinforcements convey highly defined and well-branched perfect nanostructures obtained through repetitive branched monomer iterative protection and deprotection in contrast to hyperbranch polymeric skeletons. Rationally reconfigured dendrimeric/dendritic polymers are used for drug delivery and catalysis and making light-emitting materials [1, 2]. Today, dendrimer chemistry and catalog of dendrimers offer templates for organic-inorganic hybrid nanomaterials imparting diversified and captivated utility in modern S&T. Hyperbranch polymers are 3D globular low viscous and highly soluble template used in making dendrimer-based organic/inorganic nanohybrids. Organic-inorganic nanohybrids are reconfigured through hyperbranched dendrimeric matrix to get mono-/bimetallic, bimetallic alloys and core/shells. Dendritic hyperbranch polymers and dendrimers with 3D globular arrangement and spherical outline are found to offer high branching density and branching at each repeating unit, which imparts exclusive features like lower viscosity and high solubility/functionality than linear counterparts. Advanced dendritic matrixes blend reconfigured organic/inorganic frameworks via good skeletal processing, thus offering special developed advantageous features like superior elasticity, light-weight, impassive resistance, robust strength, chemical resistance, and thermal stability. Reinforced hyperbranched dendritic matrixes own linear segments of globular end functionality valuable for making many organic-inorganic nanocomposites [2]. Assorted nanohyperbranched composites with unique globular contour with functional end groups are obtained through organic-inorganic dendrimeric templates like poly-amidoamine-reinforced nanogold particles, nanocarbon hybrid sols and heterogeneous nanostructures [2]. Intrinsic void-reinforced nanoparticles and metal clusters with enhanced stability are exploited for catalysis, adsorptions and photodetection besides being used in developing antimicrobial sensors/agents [1]. Recent advancement in nanotechnology aids to induce “disordered-to crystalline” features and perform numerous structural reinforcements a way from metal aggregate to nano-crystals in the resultant clusters/matrixes that are especial for electro-catalytic usages [1, 2]. Reinforced carbon black matrix is used for air CO₂ absorption/desorption better than Excellion™ ion-exchange membranes.

5. Controlled practices for reconfiguration

“Click” chemistry is found to control reconfigurations or modifications and facilitates stimulus detachment through characteristic porous dendrimeric links so as to yield assorted structures like fine layer-by-layer films, nanoparticles, nanosheets, nanowires and nanotubes especially used for optoelectronic nanodevices [2]. Reinforced dendritic architectures with linear, cross-link and chain-branching can afford many features like open-space functionalization and organize topology, copolymeric hybridization and terminal grafting. Versatile dendritic reinforcement motivates innovative R&D beyond predicted applications in many industries. Hyperbranch supramolecular polymer-based reinforced material matrixes offer sophisticated chemical and biological utilities. Nonmaterial reconfigurations and nanostructure reinforcements are pivotal

themes in today's scientific and technology advancement. Rationally developed nanomaterials/structures have vividly amended characteristics viable for assorted utilities, viz. electric tools, optoelectronic devices, biosensor/biomarker, photodetector, solar cell, quantum dots and plasmonic modules. At nanodimensions, the interfacial phase interaction gets better without changing matter itself; instead, it has shown innovative properties like electrical conductivity, insulation, boosted reactivity, elasticity and superior/robust strength, which is missing in micro-/macroscale counterparts [1–4, 6, 7]. These nanocomposites have multiphase combination of two/more components and one or more fillers of particles, sheets and/or fibers in their reinforced matrixes. Certain nanocomposites are reinforced through numerous progressively designed alterations in material matrixes and novel comprehensive techniques thrust interdisciplinary R&D in chemistry, physics, biology and biotechnology besides paving the way for business breakthroughs in current S&T developments [1]. Reinforced building blocks with nanodimensions fetch practical and theoretical interests via rational reconfigured and designed innovative nanocomposites owing to their extraordinary physicochemical characters and preset functionality [2]. R&D findings through inventive analytical trends and developments in nanocomposite chemistry with compiled data and analysis may aid in the exploration of stimulated reinforcements in nanocomposite matrixes [26, 28].

Nanocomposite/nanostructures reconfigured through biomatrixes faced intricate tasks like choice, combinatorial paths, modified synthesis and shaping of proper materials. Thus, plant tissues like cellulosic matter and animal components like bones/cartilage are reinforced at nanodimensional hierarchy. Morphological likeness of lignocellulose, hemicellulose and lignin matrixes enables its vast reconfigurations in developments of nanostructures/composites, which acted as viable alternatives in modern drug delivery and tissue engineering scaffolds (for regeneration of bones and cartilages) besides being used in cell-attached proliferated inductions. Biomimetic composites are being reconfigured through reinforcement of natural polymers like chitin and cellulose with inorganic materials like calcium phosphate for use in biomedical applications. Advanced nanotechnology paves the way for prospective capability across a broad spectrum of applications. The advancements in the field of nanotechnology have generated many reinforced material blends, alloys, matrixes and composites offering contemporary functional applications over other known counterparts [1].

Nowadays, specially sophisticated designing and targeted tailor/engineer morphologies are facile to induce at any (0D, 1D, 2D, and 3D) nano-dimensional scales with structure-property dependent remarkable parameters and controllable interfacial area, e.g., many onset non-bulky size-dependent quantum dots and polymeric nano-composites for industrial and environmental applications [1, 2]. Rationally reinforced polymer-based nanocomposites are best options to usual polymeric fillers and blends that appeared as a staple part of modern plastics. Nanotechnological frontiers in the twenty-first century seek better optimized composite combinations with innate synergistic utility; thus, material and functional devices need to be reinforced or reconfigured. Thus, nanotechnological reinforcements are solely dependent on mechanical augmentation of matrixes as substitute for existing counterparts. Benign or biodegradable nanocomposites reinforced through green polymers like cellulosic and chitosan matrixes are potential options to petroleum-derived non-eco-friendly thermoplastic polyolefin nanoclusters [7, 13, 27]. Reconfigured polymeric nanocomposites with exclusive mechanical, physicochemical, thermal, electrical and barrier properties and fire-retarding properties emerge as innately prospective in making exterior/interior and underbonnets, coating and components of automotive [1–4, 6, 7]. A Global Strategic Business

Report stated that the world's nanocomposite automotive market may exceed over one billion pounds in this decade with an ever robust demands in futures. Green nanocomposites obtained via reinforcements of clay, nanocarbon and other nano-fibers are beneficial than usual counterparts due to boosted mechanical, electrical and thermal barriers, besides high tensile force, more deflection temperature and flame retardations [1, 29]. Certain polymer-derived nano-material matrixes are found to possess unchanged innate features, viz. native power, viscosity and parallel optic potential by virtue of legitimated morphological reinforcements comprising thousands of hoard layers at nano-scale ensuing exfoliation and dispersion all over surfaces [2]. Reconfiguration further upshots degree of exfoliation in resultant nanostructures ultimately offering greater surface area with improved performance [2, 19, 20].

6. Challenges in designing/reinforcement of composite/matrix

Certain major challenges of composite materials are mentioned as follows:

- Need systematic and progressive interactive engineering approaches for applying various methodological technologies so as to yield optimal material characteristics with aiming targeted composite/hybrid matrixes.
- Require critical investigative analysis of physical, chemical and mechanical properties of each constituent and resultant composites/hybrids.
- Necessary to formulate some properties in resultant composite/matrix as optimized and precise with respect to its operational conditions.
- Focus to comprehend consequential manufacturing and compositional parameters of composite/matrix.
- Aim to develop meticulous and progressive combinatorial computational techniques with optimized study for expected efficiency/capacity at varied functioning conditions.
- Target to epitomize robust inhomogeneous properties in procured significant composite.

7. Prospective progress of rationally reinforced matrixes

Several challenges needs to be tackled during matrix reconfigurations and nano-composite fabrication/progressing, and this allows progressive rational designing as per desired applications. The chemical interactions that exist in resultant matrix reinforcement during its fabrication and later in its usage are to be checked via micromechanics to provide a rational basis for its designing. Intrinsically strengthened composites are obtained through various reinforced materials like graphene, nanocarbon and nanometals, which are found superior than counterparts. Reconfigured multiscale hybrids own better load reassignments at reinforced interfaces achieved via tailored interfacial shear strengthens imparting stiffness, heat protection, impactive compression and better threshold load bare. Various automotive utility needs reconfigured biopolymer-derived nanocomposites at lower cost and end-use components.

8. Innovative breaches in applicability of reinforcement materials

Some innovative breaches in applicability of rationally reinforced materials are observed that are mention as follows:

- Nanometal reinforcement in cellulose matrix is attenuated through synergy of constituting materials so as to derive innate advantageous properties of components by diverse preparatory techniques.
- Reconfigured metal nanomatrixes of chemically integrated cellulosic templates with certain novel functionalities in the ensuing composites are best exploited for filler purpose. Such nanometallic reconfigured cellulose-derived matrixes with multifaceted features have not been explored extensively and thus need to be attended.
- The basic physicochemical interactions found in such components that viably optimize innate properties are less studied.
- Nanocomposite formations significantly alter and improve the innate properties of components via multiphase reinforcements.
- Advance nanotechnology aids in reconfiguration of various materials into sole composite imparting advantageous and optimized features as per the industrial needs.
- Assorted constituting textures and dimensional comprising phases of host matrixes via their innate bonding control mechanical stability and properties of resultant nanocomposites, e.g., nanometal/metal oxide dispersions in ceramics or vitreous.

Acknowledgements

The author is thankful to Head, PGTD of Chemistry, R.T.M. Nagpur University, Nagpur, for laboratory facilities and to the Vice Chancellor, Nagpur University, Nagpur, for the sanction of research project work under University Research Project Scheme, awarded vide No. Dev/RTMNURP/AH/1672 (9) dated September 24, 2016.

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References

- [1] Dongre RS. Rationally fabricated nanomaterials for desalination and water purification. In: Book Novel Nanomaterials. Vol. 1. Croatia: In-Tech Open Publisher; 2018. pp. 348-366. DOI: 10.5772/intechopen.70149
- [2] Dongre RS. Biological activities and application of marine polysaccharides. In: Marine Polysaccharides in Medicine. Vol. 1. Croatia: In-Tech Open Publisher; 2017. pp. 181-206. DOI: 10.5772/65786
- [3] Yi X-S, Shanyi D, Zhang L, editors. Polymer matrix materials. In: Composite Materials Engineering, Volume 1: Fundamentals of Composite Materials. Singapore: Springer; 2017. pp. 147-168. ISBN: 978-981-10-5696-3
- [4] Luo YF. New developments in hi-tech synthetic fibers. *Hi-tech Fiber & Application*. 2000;25(4):1
- [5] Kotek R. Recent advances in polymer fibers. *Polymer Reviews*. 2008;48(2):221
- [6] Shaghaleh H, Xu X, Wang S. Current progress in production of biopolymeric materials based on cellulose, cellulose nanofibers, and cellulose derivatives: Review. *RSC Advances*. 2018;8:825-842. DOI: 10.1039/C7RA11157F
- [7] Huang X, Zheng S, Kim I. Hyperbranched polymers & dendrimers as templates for organic/inorganic hybrid nanomaterials. *Journal of Nanoscience and Nanotechnology*. 2014;14(2):1631-1646. DOI: 10.1166/jnn.2014.8750
- [8] Ebrahimi F. Nanocomposites: New Trends & Developments. Croatia: In-Tech; 2012. DOI: 10.5772/3389
- [9] Komarnenei S. Nanocomposites. *Journal of Materials Chemistry*. 1992;2:1219-1230
- [10] Prud'homme R, Ozbas B, Aksay I, Register R, Adamson D. Functional Graphene? Rubber Nanocomposites. U.S. Patent 7,745,528, 2010 (Filed 2006). Assignee: The Trustees
- [11] Netravali AN. Green composites: Current trends and developments. In: Proceeding of MACRO-04. Turuvanthapuram, India; 2004
- [12] Klemperer D, Sperling H, Utracki A. Interpenetrating Polymer Network. Washington DC, USA: American Chemical Society; 1994
- [13] Barham PH, Leller A. The relationship between microstructure and mode of fracture in polyhydroxybutyrate. *Journal of Polymer Science: Polymer Physics*. 1986;24(1):69-77
- [14] Leo Baekeland. "Plastics. UK history site. 28 June 2000. New Chemical Substance" (PDF). The New York Times. Princeton University; 06 February 1909
- [15] Netravali AN, Chabba S. Composites get greener. *Materials Today*. 2003;6:22-29
- [16] Chabba S, Netravali AN. 'Green' composites using modified soy protein concentrate resin and flax fabrics and yarns. *Japan Society of Mechanical Engineers*. 2004;47(4):556-560
- [17] Chamis CC. In: Piuddemann EP, editor. Interfaces in Polymer Matrix Composites. New York: Academic Press; 1974
- [18] Piggoti MR. Relations between and fiber-polymer interface properties. In: Proceedings of ASC 6th Technical Conference. 1991. pp. 725-731
- [19] Davis ME. Ordered porous materials for emerging applications. *Nature*. 2002;417:813-821. DOI: 10.1038/nature00785

- [20] Kiba S, Suzuki N, Okawauchi Y, Yamauchi Y. Prototype of low thermal expansion materials: Fabrication of mesoporous silica/polymer composites with densely filled polymer inside mesopore space. *Chemistry, an Asian Journal*. 2010;5:2100-2105
- [21] Bănică F-G. *Chemical Sensors and Biosensors: Fundamentals and Applications*. Chichester, UK: John Wiley & Sons; 2012. p. 576
- [22] Anderson M, Tilman AM. Acetylation of jute: Effects on strength, rot resistance, and hydrophobicity. *Journal of Applied Polymer Science*. 1989;37(12):3437-3447
- [23] Sanadi AR, Young RA, Clemsons C, Rowell RM. Recycled newspaper fibers as reinforcing fillers in thermoplastics: Part I - Analysis of tensile and impact properties in polypropylene. *Journal of Reinforced Plastics and Composites*. 1994;13(1):54-67
- [24] Goriparthi BK, Suman KNS, Rao NM. Effect of fiber surface treatments on mechanical and abrasive wear performance of polylactide/ jute composites. *Composites Part A: Applied Science and Manufacturing*. 2012;43(10):1800-1808
- [25] Okubo K, Fujii T, Yamashita N. Improvement of interfacial adhesion in bamboo polymer composite enhanced with micro-fibrillated cellulose. *JSME International Journal*. 2005;48(4):199-204
- [26] Graupner N, Herrmann AS, Mussig J. Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics & application areas. *Composites Part A: Applied Science and Manufacturing*. 2009;40(6-7):810-821
- [27] Nakagaito AN, Yano H. Novel high-strength biocomposites based on microfibrillated cellulose having nano-order-unit web-like network structure. *Applied Physics A: Materials Science & Processing*. 2005;80(1):155-159
- [28] Silva MJ, Sanches AO, Medeiros ES, Mattoso LHC, McMahan CM, Malmonge JA. Nanocomposites of natural rubber and polyaniline-modified cellulose nanofibrils. *Journal of Thermal Analysis and Calorimetry*. 2014;117:387-392
- [29] Nakagaito AN, Iwamoto S, Yano H. Bacterial cellulose: The ultimate nano-scalar cellulose morphology for the production of high-strength composites. *Applied Physics A: Materials Science & Processing*. 2005;80(1):93-97