National Conference on Behavioural Economics and Intelligent Decision Systems for Climate Change and Sustainable Development
Journal of Advanced Research in Alternative Energy, Environment and Ecology
Volume 13, Issue 1&2 - 2026

Review Article

Future Perspectives of Clay Based Nanocomposites as Sustainable Materials

Nisha Sharma[1], Arun Kaushal[2], Snehsheel Sharma[3], Jitendra Basrani[4], Ganesh kumar[5]

[1]Professor (chemistry), Department of Physical Sciences, Sant Baba Bhag Singh University, Jalandhar, Punjab, India
[2]MSc Student, Department of Physical Sciences, Sant Baba Bhag Singh University, Jalandhar, Punjab, India
[3]Associate Professor, Department of Mechanical Engineering, Khalsa College of Engineering & Technology, Amritsar, India
[4]Associate Professor, Department of Mechanical Engineering, Poornima University Jaipur, India
[5]Assistant Professor, Department of Chemistry, SGGS Khalsa College, Mahilpur, Hoshiarpur, Punjab, India
DOI: https://doi.org/10.24321/2455.3093.202603

I N F O

Corresponding Author:
Nisha Sharma, Department of Physical Sciences, Sant Baba Bhag Singh University, Jalandhar, Punjab, India
E-mail Id:
nishi.hpu@gmail.com
Orcid Id:
https://orcid.org/0000-0001-6452-2965
How to cite this article:
Sharma N, Kaushal A, Sharma S, Basrani J, Kumar G. Future Perspectives of Clay Based Nanocomposites as Sustainable Materials. *J Adv Res Alt Energ Env Eco* 2026; 13(1&2): 177-187.

Date of Submission: 2025-10-04
Date of Acceptance: 2025-11-01

A B S T R A C T

Environmental toxicity and prevailing health sector issues raised thereafter have sensitised research communities to provide some sustainable solutions. Advanced materials with intelligent behaviour are such fascinating materials to address some environmental and health issues. Among these nanocomposite hydrogel matrices made of naturally occurring polysaccharides and nanocomponents composed of metal based nanoparticles, metal oxides, organic, carbon and clay have acquired prime position owing to their advanced and tunable characteristics as well as their biogenic origin. Nanocomposites being advanced materials possess various superior properties such as improved mechanical/tensile properties, porosity, thermal stability, resistance toward chemical degradation and re-usability. Such properties are mainly incorporated in the composite matrix due to nano components of reinforcing materials added. These materials find a diverse range of applications such as tunable and sustained drug delivery system, bone/tissue engineering matrices, food packaging film, bioelectronics, management of tissue wounds, bio-imaging, energy storage, water treatment, biosensors and industry aligned materials depending upon their core characteristics. Polysaccharides provide an encapsulating system for nanoparticles to form a hybrid composite with integrated properties of all components. The Present study focuses on the properties and applications of polysaccharide based nanocomposite with special attention given for clay based nanocomposites as sustainable materials in different fields.

Keywords: Nanocomposite, Hydrogel, Clay, Drug Delivery Systems, Advanced Materials

Copyright (c) 2026: Author(s). Published by Advanced Research Publications

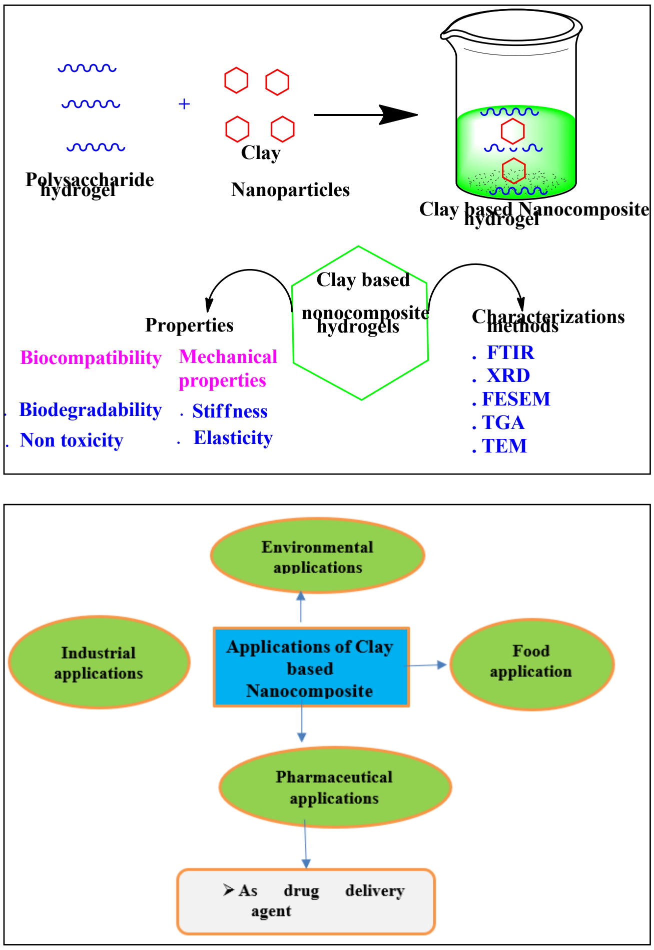

Figure 1.Flow chart regarding applications of clay-based nanocomposite hydrogel

Introduction

There are various catastrophic changes, such as global warming, climate change, and increased frequency of natural disasters, that the earth has been experiencing in the recent two decades which have resulted in prominent environmental toxicity in every sector. There is an urgent need for sustainable and eco-friendly methods and materials which could facilitate environmental monitoring/sensing and remediation of environmental pollutants. Conventional petrochemical-based personal and industrial materials have imposed diverse negative impacts on the environment, such as toxic emissions and nonbiodegradable pollutants, as witnessed by different researchers. Development of new materials with improved physiochemical properties, affinity, enrichment capacity, selectivity, and sustainability is an important topic of research that has sparked the urgency of advanced materials based on natural origins. Nanotechnology is said to have the ability to significantly alter existing methods and materials through developing new materials, remediation/treatment procedures, and monitoring sensors. Environment-friendly advanced materials derived from natural resources and improved with nanoparticles are one of the fascinating candidates for a sustainable future.[1]

Composites are engineered or naturally occurring solid materials composed of two or more constituent materials, each having its own significant characteristic to create a new substance with superior properties than the original materials in a specific finished structure. Nanocomposites are the solid combination of a bulk matrix and nano-dimensional phase(s) which differ in properties due to dissimilarities in structure and chemistry.[2] Nanocomponents (inorganic or organic fillers) incorporated must exhibit dimensions in the nanometre range (from 1 nm to 10–9 nm) in at least one phase.[3] In a composite matrix, nanocomponents need not necessarily be of controlled size, but in a nanocomposite, reinforcing material must have nanoscale dimensions with mandatory distinct inherent behaviour owing to their size.

Commonly natural, synthetic and combinations of natural and synthetic polymers are used to form nanocomposite matrices. The natural polymers used in composite formulations are normally polysaccharides, natural hydrocolloids, starches, exudate gums, pectins, and proteins.[3,4] Common nanofillers/additives used for nanocomposite fabrication include metal ions, metal oxides, solid layered clays, synthetic polymer nanofibers, cellulose nanofibers, and carbon nanotubes.[2,5] Among inorganic nanofillers, layered silicates have been utilised prominently in the packaging industry due to their abundance in nature, low cost, and ability to enhancefinished product properties under a relatively simple processing setup.[6] Nanocomposite is considered as a matrix or combination, which is composed of different materials with improved properties such as good tensile/mechanical and thermal[7], electrical, electrochemical, and optical behaviour, which are significantly different from the individual components. Structurally, nanocomposites are composed of two parts: a continuous phase and a discontinuous phase, or reinforcing phase. Continuous phases are the main building blocks of nanocomposites derived from metal, polymer, or a ceramic matrix. Discontinuous phases/nano-fillers are nanosized materials which are dispersed within a continuous phase. Polymeric matrix nanocomposites are mainly composed of natural polysaccharides and exudate gums and are the most elaborated materials in the current scenario with respect to their green origin and tunable characteristics, which have been further augmented by the incorporation of nanocomponents of choice as well as eco-friendly preparation methods.[8] Natural polymer-based nanocomposites have special characteristics aligned with sustainability, such as biodegradability, non-toxicity, durability, stability, and functionalisable reaction sites.[7,9]

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

Graphical abstract

Nanocomposite hydrogels are defined as water-swollen materials composed of a polymer matrix and nanoparticles, both organic and inorganic, metals, metal oxides, and clay as reinforcing materials into a biopolymeric base matrix, which includes polysaccharides such as starch, chitin, alginate, lipids, and proteins.[10] Reinforcing materials incorporated in the gel matrix are primarily in nanoscale dimensions and possess special characteristics attributed to their size, which in turn modulate the behaviour of polymeric matrices.[8] There are primarily covalent or physical interactions which bound the gel matrix and reinforcing materials together. The development of nano-biocomposites, or the dispersion of nano-sized filler into a biopolymer matrix, is one of the most promising strategies for improving uncontrolled swelling, poor mechanical barriers and thermal properties of biodegradable natural materials.[11]

Properties Of Nanocomposites

Nanocomposites have acquired a distinct place in material sciences due to their characteristic properties, such as mechanical/tensile strength, stability, optical, electrical, and thermal properties, etc., which decide their end use.[12]

Mechanical /Tensile Strength

The mechanical and tensile behaviour of any material is a very crucial property which decides the end use of engineered materials. This is a crucial property of composite material that assists in outdoor applications such as structural frameworks for automobiles, machinery, construction materials, and the formation of ropes, wires, textiles and industrial materials.[7] Experiments have revealed that polymer/layered silicate nanocomposite-based films possess improved mechanical, barrier, thermal, and moisture adsorption properties, thus making them suitable for packaging applications.[13]

Porosity

Porosity decides how well the products will last long and how many empty voids are present in it. Porosity is a crucial characteristic for materials used in pharmaceutics, ceramics, metallurgy, materials manufacturing, petrophysics, and hydrology. Porosity is the main property involved in the formation of biomedical products such as biomedical implants and wound dressings for early recovery since it facilitates continuous oxygen supply and removal of fluid from healing wounds.[7,8] Various fillers, especially clays, when incorporated into the polymeric coatings, improve their barrier properties by reducing their permeability and increasing the length of the diffusion pathways for oxygen and water species.[8]

Elasticity

Elasticity is the ability of a material to resist a distorting influence and to return to its original size and shape when that influence or force is removed. Like porosity, elasticity also has a very crucial role, especially in biomedical implants. Clay-based nanofillers act as good surface cohesive agents, thus facilitating the joining of one part of the material to another part, and clay-based nanocomposites have improved elasticity as compared to the base composite matrix.[8,14]

Thermal and Chemical Stability

Thermal stability is a crucial property of material since it decides the applicability of material and resists the effect of temperature fluctuation. When materials are heated, their size and volume increase in small increments, a phenomenon known as thermal expansion. Fine advanced ceramic materials have low coefficients of thermal expansion – less than half those of stainless steels. Polysaccharide-based nanocomposites are used in the formation of various products, such as packing products, and sustain temperature variation due to the nano component. It has been observed that clay modulates thermal decomposition curves of the polymeric matrix, and the residue content during thermal decomposition varies with the clay loading. Clay-embedded nanocomposites with 75 wt.% to 40 wt.% clay loading, respectively, had shown residue up to 6.7 wt.% to 23.2 wt.% after decomposition in two matrices.[7] It has been documented that during decomposition of clay-based biopolymeric nanocomposite, partial dehydroxylation of clay was observed at the second and third decomposition stages.[8] Such materials are applicable for industrial applications where temperature fluctuation is continuous.

Types Of Nanocomposites

Nanocomposites have been broadly classified as natural polymer-based nanocomposites (NPN) and synthetic polymer-based nanocomposites (SPN). NPN includes materials fabricated through reinforcement of nanoparticles and/or nanofibers in a natural polymer matrix. Several widely used natural biopolymers, including cassava starch[15], chitosan, collagen, cellulose, silk fibroin, alginate[16], and polysaccharide gums[17], have been utilised in literature for nanocomposite formation owing to their natural origin and biocompatibility behaviour. Such polysaccharides are, although, mechanically labile, and their tensile behaviour could be improved through the functionalisation of the matrix, either through graft copolymerisation or through encapsulation of nanoparticles as reinforcing materials. SPMs are composed of synthetic polymeric

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

materials such as polycaprolactone (PCL), poly (lactic-co-glycollic) acid (PLGA), polyethylene glycol (PEG), poly (lactic acid) (PLA), and polyurethane (PU), polystyrene, PP, polyesters, etc.[14] A diverse array of nanofillers, such as nano hydroxyapatite (nHA), nano zirconia (nZr), nano silica (nSi), silver nanoparticles (AgNPs), nano titanium dioxide (nTiO2), graphene oxide (GO), and carbon nanotubes (CNT), are commonly used as reinforcing nanocomponents in natural and/or synthetic polymer matrices.[2] Such nanofillers improve the structural and functional characteristics of the resultant nanocomposite matrix. Glass fibre reinforced composites, glass and other synthetic fibre-reinforced plastics possess high specific strength, although such materials are limited in use owing to their higher associated production cost. In one study, the influence of nanoclay in polyester resin-based composites reinforced with coir fibres had been evaluated.[15] The addition of nanoclay to the coir fibre-reinforced composites exhibited considerable enhancement of the mechanical properties of the resultant matrix, which is a cost-effective, eco-friendly substitute in place of glass fibres.[17] CNTs incorporated in a synthetic polymeric matrix upgrade their mechanical and electronic properties, which could be further exploited in different industrial applications such as nanoelectronic devices, chemical sensors, biosensors, and more. Since CNTs are electrically conductive, they are therefore suitable for applications that require the ability to discharge electrostatic potentials.[6] Apart from these nanofillers, graphite, metal chalcogenides, clays and layered silicates (montmorillonite, hectorite, saponite, fluoromica, fluorohectorite, vermiculite, magadiite, and kaolinite), metal phosphate [$Zr(HPO_4)_2$], and layered double hydroxides [e.g., $Mg_6Al_2(OH)_{16}CO_3.nH_2O$] have also been utilised as nanofillers for polymer-layered nanocomposite fabrication.[6] Among the inorganic nanoparticles, clays and layered silicates are the most common nanofillers owing to their natural abundance, sustainability, and natural intercalation characteristics. Among the layered silicates, montmorillonite (MMT) is most intensively studied for its high modulus of clay platelets and ready availability in large amounts from nature.[11,13]

Clay Matrix Nanocomposite

Clay is an excellent reinforcing material for the synthesis of nanocomposites. Chemically, clay is a naturally occurring aluminium silicate composed primarily of fine-grained minerals. Clay has a crystalline structure consisting of bi-dimensional layers where a central octahedral layer of either alumina or magnesia is joined to two external tetrahedrons of silica in such a way that the oxygen ions of the octahedral layer also belong to the tetrahedral layers.[14] Clay is basically aluminium silicate and possesses alkali and/or alkaline earth metals. A typical approximate composition of orthoclase is $K_2O.Al_2O_3.6SiO_2$.. Clay is either found at its origin sites, or it can be carried by rivers and deposited elsewhere. When transported by water, the particles continue to be ground finer and finer by the action of other rocks. During the transport process, clay particles got separated according to size. As a result, clay is a major component of soil all over the world, with a variety of properties according to the precise conditions that applied during its formation.[18] Clay minerals are hydrous aluminium phyllosilicate minerals composed of aluminium and silicon ions bonded into tiny, thin plates by interconnecting oxygen and hydroxyl ions. These plates are tough but flexible, and in moist clay, they adhere to each other. The resulting aggregates give clay the cohesion that makes it plastic. The dispersion of clay in a polymer matrix is a crucial factor in producing high-performance nanocomposites. It has been found that clay nanofillers show good dispersion withinthe matrix, thus making the resultant matrix as hydrogel.[8] The first commercial example of clay-based polymeric nanocomposites used in automotive applications was clay–nylon-6 nanocomposites used for making timing belt covers. Organically modified clays dispersed in a nylon-6–polymer matrix greatly improved the dimensional stability and the barrier properties. Mechanical properties of polymer-clay composite got improved by the incorporation of clay nanoparticles which act as a barrier to the diffusion of water and oxygen through the composite film. Due to the exfoliate ability of clay, polymer–clay composites in a 2:1 proportion of different clays, such as montmorillonite, laponite and hectorite, result in optimal distribution in the matrix.[15]

Improvement in barrier resistance in nanocomposites plays an important role in beverage applications. When the layers are delaminated, it increases the effective path length for molecular diffusion, and the path becomes highly tortuous to reduce the effect of gas and moisture transmission through the film.[19,20] Based on the barrier properties, nanocomposite packaging films made from polyethylene terephthalate (PET) have been studied as replacements for conventional polymer films.[21,22] Many polysaccharide-based nanocomposites possess film-forming properties that render them suitable for the preparation of membranes with different characteristics. Such membranes found practical applications in pharmaceutics, medicine, agriculture, the food industry and different industrial processes. Silane-modified nanoclay when crosslinked with functionalised starch (starch phthalate) notably improved the compressive modulus and strength of hydrogel up to twice by the addition of nanoclay. The increase in the mechanical properties was due to interaction between the amine groups present on the nanoclay and the hydroxyl and ester groups present on the modified starch.[23] Chitosan-intercalated montmorillonite clay nanocomposites display electroresponsive behaviour and a super-swelling nanocomposite network structure. This matrix had minimal

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

cytotoxicity and improved gel strength and thermal stability when used at the optimal concentration of 6%, thereby making them suitable candidates for biomedical applications.[14]

Applications Of Nano Composites

Nanocomposites, owing to their advantageous properties, are extensively used as superior-strength fibres, films, UV protection gels, drug delivery systems, fire retardant materials, anti-corrosion barrier coatings, lubricants and stretch paints and sustainable construction materials.[14] Polysaccharide-based nanocomposite hydrogels possess a mixture of properties such as biodegradability, biocompatibility, permeability, hydrophilicity, and non-toxic and non-immunogenic behaviour owing to the natural polymeric matrix and improved properties attributed to the nanocomponent included withinthe matrix, which in turn increases the horizons of polysaccharide nanocomposite hydrophilic systems.[24]

Pharmaceutical Applications

As Drug Delivery agent

Drug delivery systems include formulations that have been created for the delivery of pharmacological agents into desired regions in a reliable manner. Release of drugs to the target zone is crucial for both more effective treatment and reducing side effects. This could be achieved through the synthesis of appropriate drug delivery systems which could simulate a natural biological environment, facilitate easy access to the target organ and have minimal toxicity associated with them. Clay-based nanocomposites acquire a prime place for controlled drug delivery.[17,25] Hydroxyapatite (HA)/collagen alginate nanocomposite has been used in bone repair as well as delivery of drugs with improved behaviour. Nanocomposite has been combined with a bone formation protein. Furthermore, HA/collagen scaffolds with inherent porous structures assist in fibroblast growth factor-2. Such drug-releasing systems provide better results by inducing the regeneration of cartilage and bone in *in vivo* models. Apart from these, HA/CH nanocomposites have also been used as a drug-delivery matrix, and precise release of vitamins has been achieved from the gel matrix.[26] Anirudhan et al. have synthesised a montmorillonite/N-(carboxyacyl) chitosan-coated magnetic particle (Mt/CACh-MP)-based drug delivery system for *in vitro* controlled delivery of paracetamol through the hot intercalation technique. The newly fabricated matrix had been characterised by FTIR, SEM and XRD methods. Drug isotherms demonstrated multilayer adsorption within the matrix and showed 84% drug loading at pH 6. Targeted and controlled drug administration can be facilitated by mt/CACh-MP because of its significant swelling capacity.[s] Mohamed Mousa et al. have suggested that clay acts as a bioactive additive which enhances cellular functions such as adhesion, proliferation and differentiation reported during osteogenesis.[28] Nagahama et al. have synthesised injectable gel based on self-assembling PLGA-PEG-PLGA copolymer (P3k) micelles and clay nano discs (CNDs) for controlled release of doxorubicin (DOX). From a single injection of hybrid gel, long-term sustained release of DOX had been achieved, thus providing sustained antitumor activity in vivo and decreasing the repeated use of harsh chemotherapeutics. It had also been observed that these hybrid gels assist in decreasing the size of the tumour drastically as compared to the control, where mice were treated with PBS and free of DOX. Additionally, a gradual decrease in tumour volume was observed in mice treated with P3k/CND/DOX hybrid gel without any associated dermatitis.[29]

Bone Tissue Engineering Applications

Tissue engineering aims to support tissue regeneration and growth of healthy cells or create materials that can replace damaged tissues. Materials developed in this field should include specific morphological or structural characteristics for application. In this context, nanocomposites have shown good mimicking behaviour towards the natural morphology of the extracellular matrix surrounding cells, thus making them suitable for the promotion of repair of tissue structures.[26,30,31] Nanocomposites could also be used for tissue repair and minimise the immunological responses due to their biocompatibility. There are various nanocomposites generated from biorenewable resources used in bone-tissue engineering.[32] For bone defect regeneration, Zhai et al.[33] developed a poly(4-acryloylmorpholine) laponite-based nanocomposite hydrogel with bioactive ion release. It exhibited a suitable environment for cell growth and excellent mechanical properties. Due to the gradual release of the clay's intrinsic Mg^{2+} and Si^{4+} ions, nanocomposite hydrogel supported ALP production by primary rat osteoblasts. Therefore, following implantation *in vivo*, new bone formation is stimulated. Micro-CT analysis and reconstructed 3D images demonstrated that nanocomposite hydrogel with 5% of clay stimulated bone growth in the tibia defect in comparison with the control.[33]

Biosensors and Actuators

Stimuli-responsive hydrogel-based nanocomposites embedded with nanoclay particles demonstrate multifunctional characteristics and thus could be used as biosensors and soft robotic actuators, which show quick responses with respect to fractional changes of temperature, pH, and light, as well as magnetic and electric fields.[34] Gao et al. reported on robust poly(N-isopropylacrylamide-co-N-[3-(dimethylamino)-propyl]methacrylamide)/MMT hydrogel bilayers able to respond to both pH and temperature changes, resulting in reversible and repeatable curling/uncurling.[35] In another study, Yao et al. were also able to produce hydrogel strips with repeatable thermo-responsive behaviours that change their shape in water by switching the temperature rapidly between 24 and 42°C. Such biomimetic actuations of bilayer hydrogels may have the potential for applications as soft robotic actuators, sensors, and drug-delivery vehicles.[36] Tan et al. evaluated the potential of laponite-crosslinked (N,N-diethylacrylamide)-co-(2-dimethylamino) ethyl methacrylate hydrogels as temperature switches to change the optical transparency. As the temperature gradually increased, from 20°C to 40°C, the transparency of the nanocomposite hydrogels gradually decreased until slightly opaque, thus showing that colloidal laponite had the ability to change the visual gradient of thermo-responsive nanocomposite hydrogel.[37] Clay-based multifunctional nanocomposites have shown excellent thermal sensitivity, stimuli responsiveness, stretchability, conductivity and adhesive properties, thus making them suitable sensing devices in different sectors.[38,39,40]

Food Applications

Keeping in view sensitisation toward the use of eco-friendly and safer packaging materials for food products, nanocomposites are suitable materials for making safer and economic food packaging material. Food packaging materials could be fabricated through microwave, ultrasound, and electrospinning methods.[41,42] In food packaging applications, nanocomposites composed of polysaccharides and proteins such as casein, collagen, gelatin, soy protein, and wheat gluten are commonly used as the main matrix elements.[43] Biodegradable characteristics of such matrices are applicable mainly for food packaging and surface coating materials for various medical equipment, tablets, etc.[44] Films and coatings for packaging applications with antimicrobial function have been presented as an effective method to control microbial contamination in ready-made food.[45,46] The prepared material acts to block the passage of moisture, gas, and solvent as a selective barrier, as well as increasing food safety with antimicrobial properties. But poor mechanical strength of such materials limits their use. To address such shortcomings, metal oxide nanoparticles, nanoclay, metal, carbon nanofibers, and nanotubes have been doped[47,48] with the help of doping, thereby improving the chemical and physical properties of the resultant matrix.[49] Nanocomposites with zein protein are one of the excellent antibacterial food packaging[41] matrices in which nano enhancers are used to increase the mechanical performance of corn zein films. The other biopolymer, whey protein isolate, which is a byproduct of the cheesemaking industry, is also used for food packaging.[42] Although these protein films show stable mechanical properties, they have substandard tensile strength along with a high water vapour transmission profile. Such demerits could be addressed via the formation of whey protein−polymer matrices reinforced using nanoclay as nanofillers.[50] The addition of TiO_2/SiO_2 nano enhancers to biopolymer matrices like proteins not only incorporates antimicrobial function but also enhances the mechanical strength of the films. Nanocomposites that have inhibitory effects on E. coli and Salmonella typhimurium, especially in the packaging of meat, have been prepared by adding EDTA to biorenewable films comprising nisin and lysozyme.[51] Novel biodegradable starch/clay nanocomposite films synthesised through homogeneously dispersing montmorillonite nanoparticles in different starch-based materials via polymer melt processing techniques have been used as food packaging matrices. Structural and mechanical characterisations on the nanocomposite films were also performed.[43,44,45,46]

Despite so many advantages associated with nanocomposites, there are certain concerns associated with the use of nanocomposites in food packaging films. Leaching of nanocomponents through the packaging films must be thoroughly evaluated to ascertain the safety aspects.[52,53] Another important aspect to consider is the recyclability of the polymer nanocomposite materials. The evaluation was carried out through recycling tests, where conventional recycled packaging films without nanomaterials were subjected to extrusion processing in combination with increasing concentrations of nanoreinforced plastic films. Antimicrobial properties of food packaging were evaluated based on disc diffusion assay of any films of nanocomposites used in food packaging.[54]

Environmental Applications

Urbanisation, industrialisation and indiscriminate use of petrochemicals and chemical fertilisers are the leading factors for the accumulation of toxic wastes containing many poisonous chemicals, including heavy metals, toxic metalloids, polycyclic hydrocarbons (PCH) and dyes in every sector of the environment. These pollutants are released from industries of tanning, textiles, food, paper, and pharmaceuticals and chemical industries.[55] These pollutants, especially dyes and PCH, are carcinogenic in nature and pose adverse effects on the environment as well. Excessive accumulation of heavy metals damages the body's central nervous system, skin (causing dermatitis), and many biological systems. Therefore, their removal from water is essential for a healthy environment.[56, 57, 58, 59] Therefore, biopolymeric-based nanocomposite membranes with different structures and reinforcements are commonly exploited for the removal of organic dyes, heavy metals and pollutants from dirty water.[60] Contaminant enrichment methods commonly used include membrane filtration, ion exchange, chemical precipitation, absorption, adsorption and electrochemical separation.[56] Among these methods,

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

membrane-based methods are widely used because of the advantages such as low energy consumption, using very low concentrations, high purification efficiency, simple operation, high selectivity, compliance with green chemistry principles, and lower operating costs. The porous and highly polar structure of biorenewable composites provides an important advantage for water purification applications.[57] The strong interaction between polar groups and pollutants withinthe polysaccharide-based nanocomposites is the basis for good purification. Therefore, column fillers or membranes made of such biorenewable reinforcement-based composites are frequently used in water purification processes.[61] Functionalised chitosan/cinnamaldehyde nanocomposites enriched with Fe_3O_4 were synthesised as adsorbents and used to remove toxic Cr(VI) from aqueous solution. The morphological, structural, and magnetic properties of composites were investigated. The toxic Cr(VI) adsorption mechanism was evaluated by batch experiments as a function of adsorbent dosage, contact time, pH, and initial hexavalent chromium concentration. At 298 K, the nanocomposite adsorbent reached adsorption equilibrium. In another study, clay/polymer hybrid nanocomposite materials had been used for dye enrichment and removal owing to their hydrophilic structure, high mechanical strength, and better thermal stability.[14] Hosseinzadeh and coworkers studied cationic crystal violet (CV) dye enrichment using hydrogels made of kappa-carrageenan and poly(vinyl alcohol) integrated with sodium montmorillonite nanoclay. Nanoclay drastically alters the swelling behaviour of the functionalised nanocomposite matrix, declining it from 1200% to 320% due to extensive crosslinking. The effects of contact time, nanoclay concentration, pH, temperature, and ion strength on the uptake of crystal violet dye have also been investigated. The nanocomposites had a higher adsorption than the clay-free hydrogel in the same batch setup.[62] Malachite green uptake was studied using carboxymethyl cellulose/montmorillonite nanocomposites. The maximum monolayer adsorption capacity was calculated using the Langmuir isotherm model, and the adsorption process kinetic was better described by a pseudo-second-order kinetic model. Functionalised nanocomposites display higher adsorption as compared to simple hydrogels. The effectiveness of the adsorption process decreased as ion concentration increased.[63,64] There are prevalent microbial contaminants in water, such as Entamoeba histolytica, Shigella sp., and Salmonella typhi, which are responsible for dangerous waterborne infections such as diarrhoea, dysentery, and typhoid. The conventional method of disinfection is chlorination, but nowadays, this technology has become less effective since the existence of soluble organic pollutants has resulted in the formation of secondary toxic contaminants.[57] It has been documented in literature that clay-based nanocomposites showed the ability to remove various pollutants (bacteria, metals, phenol, tannic acid, pesticides, dyes, etc.) from water/wastewater.[61] Montmorillonite-polydimethylsiloxane-chlorhexidine acetate and clay-polydimethylsiloxane-chitosan-silver showed the ability to retard the growth of different bacterial strains. E. coli was also removed via bentonite clay composite modified with starch-grafted quaternary ammonium ethers. In another study, chitosan-based nanocomposites have an antimicrobial activity. Montmorillonite-chitosan nanocomposites had shown better removal efficiency of S. aureus and E. coli as compared to montmorillonite and chitosan matrix. Furthermore, E. coli was removed via nanocomposites of rectorite modified with PVA, chitosan, and sodium dodecyl sulfonate compared to the single components. High antimicrobial activity was also reached via chitosan-organoclay and chitosan-montmorillonite modified with Ag+ nanoparticles.[59] There are various clay-based

Nanocomposites are utilised as adsorbents in literature for the enrichment of dangerous toxic organic pollutants due to the existence of polymeric hydrophobic parts on the nanocomposite surfaces.[54] There is another advantage of using clay-based nanocomposites since these matrices could be compressed in the form of fine powder or tablets using the thin-coated layer methods. These methods provide an enhancement of the adsorbent reusability after adsorption of toxic contaminants.[65] Clay-polymer nanocomposites can also be used for the adsorption of toxic gases like ammonia and metallic gases such as mercury, thereby broadening their horizon in sensing of leakage issues in industrial or domestic setups. For example, chitosan-bentonite composite was used as an adsorbent for the elimination of Hg.[1] Also, a composite, synthesised from acid-activated bentonite and natural palygorskite via a polymerisation reaction between N,N'-methylenebisacrylamide and acrylic acid, was used for the adsorption of ammonia, etc.

Industrial Applications

Nanocomposites find applications in industrial sectors extensively in terms of designing advanced materials with superior properties, which is the most demanding area in the current era of continuous technological innovations, as well as the changingof society toward accessible materials with superior characteristics. Technological applications of gas separation have been increasingly developed to solve various global issues and challenges in recent years[66]. industrial setups, these materials are being used for the separation of nitrogen from the air, separation of water and CO_2 from natural gases, separation of hydrogen gas (for example, separation of H_2/hydrocarbon in petrochemical applications and separation of H_2/N_2 in nitrogenous plants), and separation of organic vapours from air or nitrogen streams. Membrane-based gas separation techniques are

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

the most commonly used methods [49]. However, when conventional membrane materials are used, one of the most important barriers may be the increase of the selectivity and decrease of the permeability and vice versa. The development of hybrid or nanocomposite membranes to overcome this problem has been one of the most promising research directions in recent years. Because nanocomposite membranes have some advantages, such as control over porosity, good mechanical stability, and ease of processing, they are attractive as an alternative material compared to conventional separation methods.[67] In technological industrial gas separation, cellulose is the most widely used renewable resource as a matrix material in nanocomposite membrane structures. Organic–inorganic nanocomposites are generally being prepared using zeolite, silica, alumina, carbon molecular sieves, etc. as additional reinforcements in the polymer matrix because these materials increase the selectivity and permeability of nanocomposite hybrid membranes. Various types of electrical properties are also enhanced.[68]

Conclusion

Nanocomposites and nanoparticle-embedded polymeric systems are advanced materials of choice in the current scenario. These functionalised materials could also be utilised as renewable, sustainable structural frameworks, biomedical devices, adsorbents and sensors depending upon their core characteristics and broad horizon of functionalisation. There are various studies conducted on functionalisation, improvisation of properties and applications of nanocomposites by different researchers globally. Such materials have shown the ability to detect pollutants, gases or other components in industrial setups, thereby assisting in ecotoxicity monitoring, which is the biggest concern nowadays. When compared to ordinary hydrogels, polysaccharide-based nanocomposite hydrogels have shown superior and new characteristics, such as better electrical, thermal, magnetic, and conductive capabilities, and are more sensitive toward external stimuli, thereby being employed in a variety of applications, including hygiene goods, biosensors, food packaging, agriculture, wound dressing, tissue engineering, drug delivery, and the removal of organic pollutants, dyes, and heavy metal ions. Apart from it, there is a need for evaluation of ecotoxicity associated with the release/leaching of the nanocomponents in the environment as well as their monitoring and alleviation methods to be devised. There are many more possibilities to explore and utilise polysaccharide-based nanocomposites for advanced applications such as energy assimilation, storage and communication, apart from more precise drug therapies.

References

1. Amari, Abdelfattah, et al. "Clay-polymer nanocomposites: preparations and utilization for pollutants removal." Materials 14.6 (2021): 1365.
2. Becker, Ole, Russell Varley, and George Simon. "Morphology, thermal relaxations and mechanical properties of layered silicate nanocomposites based upon high-functionality epoxy resins." Polymer 43.16 (2002): 4365-4373.
3. Defaye, Jacques, and Emile Wong. "Structural studies of gum arabic, the exudate polysaccharide from Acacia senegal." Carbohydrate Research 150.1 (1986): 221-231.
4. Bhatt, Akanksha, Nidhi Nainwal, and Priyank Purohit. "The impact of carrageenan on pharmascience." Current Traditional Medicine 10.6 (2024): 206-223.
5. Imeson, A. P., G. O. Phillips, and P. A. Williams. "Handbook of hydrocolloids." UK: FMC Corporation Ltd [https://www. cabdirect. org/cabdirect/20013119633] [Diakses pada 26 Januari 2019] (2000).
6. Park, Hwan-Man, et al. "Preparation and properties of biodegradable thermoplastic starch/ clay hybrids." Macromolecular Materials and Engineering 287.8 (2002): 553-558.
7. Park, Hwan-Man, et al. "Environmentally friendly polymer hybrids Part I Mechanical, thermal, and barrier properties of thermoplastic starch/clay nanocomposites." Journal of Materials Science 38.5 (2003): 909-915.
8. Hussain, Farzana, et al. "Polymer-matrix nanocomposites, processing, manufacturing, and application: an overview." Journal of composite materials 40.17 (2006): 1511-1575.
9. Park, Hwan-Man, et al. ""Green" nanocomposites from cellulose acetate bioplastic and clay: effect of eco-friendly triethyl citrate plasticizer." Biomacromolecules 5.6 (2004): 2281-2288.
10. Rinaudo, Marguerite. "Chitin and chitosan: Properties and applications." Progress in polymer science 31.7 (2006): 603-632.
11. Chivrac, Frédéric, Eric Pollet, and Luc Avérous. "Progress in nano-biocomposites based on polysaccharides and nanoclays." Materials Science and Engineering: R: Reports 67.1 (2009): 1-17.
12. Shaban, Mohamed, et al. "Adsorption properties of kaolinite-based nanocomposites for Fe and Mn pollutants from aqueous solutions and raw ground water: kinetics and equilibrium studies." Environmental Science and Pollution Research 24.29 (2017): 22954-22966.

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.202603

13. Tunç, Sibel, and Osman Duman. "Preparation and characterization of biodegradable methyl cellulose/montmorillonite nanocomposite films." Applied Clay Science 48.3 (2010): 414-424.
14. Sharma, Nisha, and Vikrant Singh Rana. "Advancement in hybrid nanocomposite hydrogels and their applications." Polysaccharides-Based Hydrogels. Elsevier, 2024. 353-403.
15. Perotti, Gustavo F., et al. "Biopolymer-clay nanocomposites: Cassava starch and synthetic clay cast films." Journal of the Brazilian Chemical Society 25 (2014): 320-330.
16. Lee, Kuen Yong, and David J. Mooney. "Alginate: properties and biomedical applications." Progress in polymer science 37.1 (2012): 106-126.
17. Mirhosseini, Hamed, and Bahareh Tabatabaee Amid. "A review study on chemical composition and molecular structure of newly plant gum exudates and seed gums." Food research international 46.1 (2012): 387-398.
18. Babaee, Mehran, et al. "Biodegradability and mechanical properties of reinforced starch nanocomposites using cellulose nanofibers." Carbohydrate polymers 132 (2015): 1-8.
19. Islam, Md Shahidul, Md Saifur Rahaman, and Jeong Hyun Yeum. "Electrospun novel super-absorbent based on polysaccharide–polyvinyl alcohol–montmorillonite clay nanocomposites." Carbohydrate polymers 115 (2015): 69-77.
20. Ates, Burhan, et al. "Chemistry, structures, and advanced applications of nanocomposites from biorenewable resources." Chemical Reviews 120.17 (2020): 9304-9362.
21. Navarchian, Amir H., Mehdi Jalalian, and Majid Pirooz. "Characterization of starch/poly (vinyl alcohol)/clay nanocomposite films prepared in twin-screw extruder for food packaging application." Journal of Plastic Film & Sheeting 31.3 (2015): 309-336.
22. Zhen, Weijun, and Youya Zheng. "Synthesis, characterization, and thermal stability of poly (lactic acid)/zinc oxide pillared organic saponite nanocomposites via ring-opening polymerization of d, l-lactide." Polymers for Advanced Technologies 27.5 (2016): 606-614.
23. Ashamol, A., et al. "Nanocomposites of crosslinked starch phthalate and silane modified nanoclay: Study of mechanical, thermal, morphological, and biodegradable characteristics." Starch-Stärke 65.5-6 (2013): 443-452.
24. Sharma, Nisha, and Vikrant Singh Rana. "A review on polysaccharide based nanocomposite hydrogel systems fabrication using diverse reinforcing materials." J. Polym. Compos 8.1 (2020): 6-17.
25. Ozkose, Umut Ugur, et al. "In-situ preparation of poly (2-ethyl-2-oxazoline)/clay nanocomposites via living cationic ring-opening polymerization." European Polymer Journal 88 (2017): 586-593.
26. Zhou, Mi, et al. "High-performance starch/clay bionanocomposite for textile warp sizing." Polymer Composites 39 (2018): E441-E447.
27. Anirudhan, T. S., S. Saranya Gopal, and S. Sandeep. "Synthesis and characterization of montmorillonite/N-(carboxyacyl) chitosan coated magnetic particle nanocomposites for controlled delivery of paracetamol." Applied clay science 88 (2014): 151-158.
28. Mousa, Mohamed, et al. "Clay nanoparticles for regenerative medicine and biomaterial design: A review of clay bioactivity." Biomaterials 159 (2018): 204-214.
29. Nagahama, Koji, et al. "Self-assembling polymer micelle/clay nanodisk/doxorubicin hybrid injectable gels for safe and efficient focal treatment of cancer." Biomacromolecules 16.3 (2015): 880-889.
30. Madhumitha, G., et al. "Recent advances in starch–clay nanocomposites." International Journal of Polymer Analysis and Characterization 23.4 (2018): 331-345.
31. Abdullah, Zainab Waheed, and Yu Dong. "Recent advances and perspectives on starch nanocomposites for packaging applications." Journal of Materials Science 53.22 (2018): 15319-15339.
32. Li, Jiali, et al. "Fabrication and characterization of starch-based nanocomposites reinforced with montmorillonite and cellulose nanofibers." Carbohydrate Polymers 210 (2019): 429-436.
33. Zhai, Xinyun, et al. "Clay-based nanocomposite hydrogel with attractive mechanical properties and sustained bioactive ion release for bone defect repair." Journal of Materials Chemistry B 9.10 (2021): 2394-2406.
34. Tipa, Cezar, et al. "Clay-based nanocomposite hydrogels for biomedical applications: a review." Nanomaterials 12.19 (2022): 3308.
35. Gao, Guorong, et al. "Synergistic pH and temperature-driven actuation of poly (NIPAM-co-DMAPMA)/clay nanocomposite hydrogel bilayers." Acs Omega 3.12 (2018): 17914-17921.
36. Yao, Chen, et al. "Smart hydrogels with inhomogeneous structures assembled using nanoclay-cross-linked hydrogel subunits as building blocks." ACS applied materials & interfaces 8.33 (2016): 21721-21730.
37. Tan, Yun, et al. "A gradient Laponite-crosslinked nanocomposite hydrogel with anisotropic stress and thermo-response." Applied Clay Science 148 (2017): 77-82.
38. Wang, Yang, et al. "Fabrication and characterization of temperature-, pH-and magnetic-field-sensitive organic/inorganic hybrid poly (ethylene glycol)-based

hydrogels." Colloids and Surfaces A: Physicochemical and Engineering Aspects 415 (2012): 68-76.
39. Chen, Lie, et al. "Anisotropic thermoresponsive hydrogels by mechanical force orientation of clay nanosheets." Polymer 192 (2020): 122309.
40. Di, Xiang, et al. "Poly (N-isopropylacrylamide)/ polydopamine/clay nanocomposite hydrogels with stretchability, conductivity, and dual light-and thermo-responsive bending and adhesive properties." Colloids and Surfaces B: Biointerfaces 177 (2019): 149-159.
41. Jha, Pankaj. "Effect of plasticizer and antimicrobial agents on functional properties of bionanocomposite films based on corn starch-chitosan for food packaging applications." International journal of biological macromolecules 160 (2020): 571-582.
42. Zhong, Yajie, et al. "Biodegradable polymers and green-based antimicrobial packaging materials: A mini-review." Advanced Industrial and Engineering Polymer Research 3.1 (2020): 27-35.
43. Bumbudsanpharoke, Nattinee, and Seonghyuk Ko. "Nanoclays in food and beverage packaging." Journal of Nanomaterials 2019.1 (2019): 8927167.
44. Murugesan, Selvakumar, and Thomas Scheibel. "Copolymer/clay nanocomposites for biomedical applications." Advanced Functional Materials 30.17 (2020): 1908101.
45. Islam, Hasanul Banna Muhammad Zukaul, Md Abu Bin Hasan Susan, and Abu Bin Imran. "Effects of plasticizers and clays on the physical, chemical, mechanical, thermal, and morphological properties of potato starch-based nanocomposite films." ACS omega 5.28 (2020): 17543-17552.
46. Mohseni, Maedeh Sadat, et al. "Green synthesis of Ag nanoparticles from pomegranate seeds extract and synthesis of Ag-Starch nanocomposite and characterization of mechanical properties of the films." Biocatalysis and Agricultural Biotechnology 25 (2020): 101569.
47. Kwaśniewska, Anita, et al. "The influence of kaolin clay on the mechanical properties and structure of thermoplastic starch films." Polymers 12.1 (2020): 73.
48. Mansour, Gabriel, et al. "Characterization and properties of non-granular thermoplastic starch—Clay biocomposite films." Carbohydrate Polymers 245 (2020): 116629.
49. Ashaduzzaman, Md, Dipti Saha, and Mohammad Mamunur Rashid. "Mechanical and thermal properties of self-assembled kaolin-doped starch-based environment-friendly nanocomposite films." Journal of composites Science 4.2 (2020): 38.
50. Nazrin, A., et al. "Nanocellulose reinforcedthermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications." Frontiers in chemistry 8 (2020): 213.
51. Nasution, H., F. Wijaya, and E. Mitro. "Characteristics of CNC reinforced cassava starch biocomposites activated with holy basil extract." AIP Conference Proceedings. Vol. 2267. No. 1. AIP Publishing LLC, 2020.
52. Sarfraz, Jawad, et al. "Nanocomposites for food packaging applications: An overview." Nanomaterials 11.1 (2020): 10.
53. Othman, Siti Hajar. "Bio-nanocomposite materials for food packaging applications: types of biopolymer and nano-sized filler." Agriculture and Agricultural Science Procedia 2 (2014): 296-303.
54. Fahmy, Heba Mohamed, et al. "Advances in nanotechnology and antibacterial properties of biodegradable food packaging materials." RSC advances 10.35 (2020): 20467-20484.
55. Moharrami, Parisa, and Elaheh Motamedi. "Application of cellulose nanocrystals prepared from agricultural wastes for synthesis of starch-based hydrogel nanocomposites: Efficient and selective nanoadsorbent for removal of cationic dyes from water." Bioresource Technology 313 (2020): 123661.
56. Abuchenari, Aliasghar, et al. "Clay-reinforced nanocomposites for the slow release of chemical fertilizers and water retention." Journal of Composites and Compounds 2.3 (2020): 85-91.
57. Abdurrahim, I. "Water sorption, antimicrobial activity, and thermal and mechanical properties of chitosan/ clay/glycerol nanocomposite films." Heliyon 5.8 (2019).
58. del Mar Orta, María, et al. "Biopolymer-clay nanocomposites as novel and ecofriendly adsorbents for environmental remediation." Applied Clay Science 198 (2020): 105838.
59. Mohammadi, Neda, et al. "Coating of sepiolite-chitosan nanocomposites onto urea increases nitrogen availability and its use efficiency in maize." Archives of Agronomy and Soil Science 66.7 (2020): 884-896.
60. Lawchoochaisakul, Sirinan, Pathavuth Monvisade, and Punnama Siriphannon. "Cationic starch intercalated montmorillonite nanocomposites as natural based adsorbent for dye removal." Carbohydrate Polymers 253 (2021): 117230.
61. de Souza, Felipe Menezes, et al. "Rheological assessment of the interaction between hydrophobic nanoclay and xanthan gum in saline environment, for application in drilling nanofluid." Research, Society and Development 9.7 (2020): e789974669-e789974669.
62. Hosseinzadeh, Hossein, Shiva Zoroufi, and Gholam Reza Mahdavinia. "Study on adsorption of cationic dye on novel kappa-carrageenan/poly (vinyl alcohol)/ montmorillonite nanocomposite hydrogels." Polymer Bulletin 72.6 (2015): 1339-1363.
63. Peighambardoust, Seyed Jamaleddin, et al. "Removal of malachite green using carboxymethyl cellulose-g-polyacrylamide/montmorillonite nanocomposite

hydrogel." International Journal of Biological Macromolecules 159 (2020): 1122-1131.
64. Sharma, Nisha, Mithu Maiti Jana, and Shweta Singh. "Role of Nanocomposite Materials for Water Pollution Alleviation Technologies." Implications of Nanoecotoxicology on Environmental Sustainability. IGI Global Scientific Publishing, 2023. 55-75.
65. Amari, Abdelfattah, et al. "Clay-polymer nanocomposites: preparations and utilization for pollutants removal." Materials 14.6 (2021): 1365.
66. Abalymov, Anatolii, et al. "Carbon nanotubes transform soft gellan gum hydrogels into hybrid organic–inorganic coatings with excellent cell growth capability." C 7.1 (2021): 18.
67. Sharma, Priyanka R., et al. "Nanocellulose from spinifex as an effective adsorbent to remove cadmium (II) from water." ACS Sustainable Chemistry & Engineering 6.3 (2018): 3279-3290.
68. Zeng, Qiankun, et al. "Polydopamine nanoparticle-dotted food gum hydrogel with excellent antibacterial activity and rapid shape adaptability for accelerated bacteria-infected wound healing." Bioactive materials 6.9 (2021): 2647-2657.