

Green Polymer Composite Films for Sustainable Food Packaging: A Review



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ABSTRACT: Food packaging involves the process of enclosing food to keep it safe from outside elements that could contaminate, harm, or decompose it while it is being transported, stored, or sold. Selection of packaging materials used play a critical role in ensuring food safety and extending shelf life. This makes the exploration of sustainable alternatives, such as Natural Fibre Reinforced Green Composites (NFRGCs), essential. In addition to packaging sustainability, NFRGCs have gained prominence in several vital applications in industries, including semi-structural, structural, automotive, aerospace, medical etc. because of their long-term sustainability. This review work focuses on the present and potential applications of green composite films intercalated with turmeric oil. It highlights the significance of the materials now in use as well as their limitations. The necessity of sustainable packaging stems from customer demand, legal pressures, and environmental concerns. Green composites are being investigated as an alternative to synthetic polymer composites due to their good mechanical properties, affordability, biodegradability, improved life cycle, and eco-friendliness. Turmeric oil-intercalated nanocomposites offer unique benefits for food packaging, including improved mechanical and barrier properties, increased antimicrobial and antioxidant properties, and potential environmental benefits. Despite challenges like cost and scalability, they represent a new frontier in packaging innovation.

KEYWORDS: Food packaging, Green composite film, Polymer, Intercalated nanostructures

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I. INTRODUCTION

Food packaging includes everything that surrounds or holds food, including boxes, bags, straws, plates, cups, and wraps. Food packaging is necessary for the transportation, storage, and consumption of food goods in an increasingly urbanized society (Lu et al., 2024). It is projected that there will be 9.7 billion people on the planet by 2050, with two-thirds residing in cities. This will lead to a rise in food needs and modifications in the ways that people consume food (Schwartz-Narbonne et al., 2023). Urban dwellers typically lead busier lives, spending less time preparing meals or grocery shopping, favoring processed foods over fresh foods, and making most of their purchases at supermarkets or convenience stores to save time. Though small businesses and conventional grocery stores are closing and being replaced by supermarkets even in underdeveloped nations, such tendencies are still evident today in high-income countries, leading to supply chains that are more heavily dependent on packaged food (Zhang et al., 2024).

Customers now must deal with serious issues related to food safety. Food quality can be impacted and accelerated by several steps in the food production supply chain, including harvesting, processing, transportation, and storage (Xu et al.,

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2024). Furthermore, fresh food that has been tainted by pathogenic bacteria creates a wide range of metabolites quickly, including volatile components, organic acids, and derivatives of sulphur (Roy et al., 2024). Food quality and safety can be directly impacted by these metabolites, as they can cause permanent alterations to the food's colour, flavour, or pH (Zhang et al., 2024). This is because food's organoleptic and nutritional properties are subject to fluctuations in environmental and physiological conditions (Xu et al., 2024).

More than before, polymer composites made of renewable and biodegradable plant-based components, primarily from forests, are becoming more and more popular as awareness of environmental degradation and the need for more adaptable, eco-friendly materials grows. These composites are commonly known as "green" materials and have a wide range of industrial uses. Green composites have a lower environmental impact and have the potential to replace polymeric materials derived from petroleum (Bhowmik et al., 2024). Governments and regulatory bodies throughout the world are implementing more stringent regulations concerning packaging materials and waste disposal. Companies that don't utilize environmentally friendly packaging run the danger of fines and legal action (Zhang et al., 2024). By proactively implementing sustainable packaging, businesses may ensure compliance with current and

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future environmental regulations and avoid heavy financial penalties (Tavassoli et al., 2023). To be considered sustainable packaging, eco-friendly materials must also be used, and the design must be simplified for optimal performance. Compact and lightweight packaging reduces waste and lowers shipping costs for businesses. As e-commerce grows, effective packing can greatly impact a business's capacity to cut expenses and its carbon footprint (Wani et al., 2024). Sustainable packaging has led to incredible advancements in material science and design. Reusable packaging methods and biodegradable plastics are only two examples of the ever-evolving category of sustainable packaging. These developments benefit the environment as well as the economy and present new opportunities for businesses to differentiate themselves from competitors (Roy et al., 2024).

Green packaging based on biodegradable composite materials is currently gaining a lot of attention from a variety of areas due to its unique qualities over typical plastics derived from petrochemicals (Venkatesan et al., 2024a). Natural composite materials are created by mixing plant fibres with natural resins to create green composites. Notably, several natural fibres, including kenaf, flax, jute, hemp, and sisal, have garnered attention globally for use in biomedical and medication delivery, bio-membranes, automotive, and industrial composting applications, in addition to sustainable food packaging systems (Doddamani et al., 2023). Given its improved qualities, green composites are a significant class of bio-composites that have received extensive research (Schwartz-Narbonne et al., 2023). To create an environmentally acceptable and sustainable composite, natural fibres are used to reinforce the biodegradable polymeric substance (Rane et al., 2024). The conventional petroleum-based composites, which are poisonous and nonbiodegradable, may be drawn to green composites (Pradhan et al., 2023). Biodegradable polymer composites replace conventional materials like steel and wood in green composites. The environmentally safe and biodegradable green composites were created using a variety of fabrication methods (Lu et al., 2024).

Turmeric, a spice that has garnered significant attention in both the culinary and medical fields, is sourced from the rhizomatous herbaceous perennial plant *Curcuma longa*, which belongs to the ginger family (Zhang et al., 2023). One of the main components of turmeric is turmeric oil (TO), which is primarily composed of ar-turmerone, widely used in medical applications due to its wide range of biological activity, particularly its antioxidant qualities (Visakh et al., 2023). The rhizome of the *Curcuma longa* plant yields turmeric oil, which has drawn interest due to its special qualities and possible uses, especially in composite films (Nowak et al., 2024). Due to its numerous health benefits, turmeric oil is a popular addition to composite films, its natural and biodegradable properties, together with its antibacterial, anti-inflammatory, and antioxidant properties, aid in the creation of high-performing, sustainable materials. Turmeric oil has the potential to significantly advance eco-friendly technologies and enhance composite film performance in a variety of industries, as research into its possible uses grows (Mondal et al., 2024).

This research aimed to investigate the moderating role of management environmental concern in the relationship between green polymer composite innovation, firm performance, and competitive competence. It demonstrated how product innovation in green polymer nanocomposites improves firm performance and competitiveness.

II. GREEN COMPOSITE IN FOOD PACKAGING

A. Green Composite Compositions

Green composites in food packaging refer to renewable, sustainable materials, that combine natural fibres or fillers with bio-based or biodegradable matrices (Raj et al., 2023). These composites aim to provide sustainable alternatives to conventional packaging materials like plastics (Raj et al., 2023). Green composite materials are innovative, eco-friendly materials combining natural fibres (hemp, bamboo, flax), biopolymers (polylactic acid, polyhydroxyalkanoates) or recycled materials (recycled carbon fibre, reclaimed wood) to reduce environmental impact. Characterized by renewability, biodegradability, low toxicity, and sustainable production, these materials offer alternatives to traditional synthetic materials. They provide benefits like reduced carbon footprint, resource conservation, waste reduction, and improved sustainability. Applications include packaging, construction, automotive and consumer goods, supporting sustainable development and minimizing environmental harm. Composites are designed to fulfil certain requirements in terms of performance, application, and demands (Moustafa et al., 2019). Natural composite materials combine plant fibres and natural resins to form a green composite. Typical materials used in green composites include:

B. Natural Fibres

These can either be cellulosic or non-cellulosic fibres. Cellulosic fibres are derived from plants such as jute, hemp, flax, or bamboo, while non-cellulosic like soy protein, casein (milk protein), and algal fibres as presented in Fig.1. These fibres provide strength, stiffness, and impact resistance to the composite (Ifeyinwa et al., 2023). The tensile strength and stiffness properties of natural fibres have been reported to be too low compared to synthetic fibre yet they are making significant progress in various industrial applications.

C. Bio-Based Polymers

These are polymers derived from renewable biological sources rather than petrochemicals. These polymers can be either biodegradable, for example (polylactic acid, polyhydroxyalkanoates, starch) or non-biodegradable (bio-based polyethylene, bio-based polyethylene terephthalate), depending on their chemical structure. The primary focus of bio-based polymer is to reduce dependence on fossil fuels and minimize environmental impact. Biodegradable bio-based polymers offer an eco-friendly alternative with their ability to break down, while non-biodegradable bio-based polymers still rely on traditional plastic properties, even though they are derived from renewable sources.



Figure 1: Types of natural fibres (Doddamani et al., 2023).

D. Fillers and Additives

These are materials added to the matrix of a composite to improve specific properties like mechanical strength, stiffness and impact resistance or modify the material's behaviour using flax, hemp, talc, silane coupling agents, natural dyes, plasticizers, clay, starch nanoparticles, or natural resins. By selecting and optimizing these fillers and additives, green composites can be engineered to meet specific performance requirements while maintaining their environmental benefits. These materials contribute to the overall sustainability of the composite by leveraging renewable resources and improving the efficiency and functionality of the product.

III. BIODEGRADABILITY CHALLENGES AND SOLUTIONS FOR SUSTAINABLE FUTURE

Green composites offer a more sustainable and often safer alternative to conventional packaging materials by combining environmental benefit with functional performance, addressing key issues such as waste management and resource sustainability making them a valuable option for environmentally conscious packaging solutions.

A. Biodegradability

Bio-nanocomposite is a naturally occurring substance that decomposes organically; its intrinsic mechanical weakness and permeability to gasses and moisture frequently limit its potential for use in sustainable applications (Dong et al., 2024). biodegradable polymers are the materials of choice, owing to their ease of breaking down into environmentally friendly substances when exposed to nature. Despite being environmentally benign, biodegradable polymers like polycaprolactone (PCL), polyhydroxyalkanoates (PHA), and PLA are not suitable for use as packaging materials due to their low barrier qualities. Their inherent structure causes gasses and tiny chemicals to permeate. Nevertheless, the barrier qualities

of biodegradable polymers are improved when they are reinforced with nanoparticles or nanofillers. The creation of biodegradable systems with enhanced barrier characteristics is one of the most optimistic goals in the design of novel materials for food packaging (Garavand et al., 2024).

Many components of green composites are biodegradable, breaking down naturally into non-toxic components and reducing environmental pollution (Karimi & Dufresne, 2014). Biopolymers consist of a chain network of macromolecules acquired from natural sources through enzymatic or chemical polymerization. These polymers have the ability to degrade through the action of enzymes and other factors (heat, moisture, sunlight) and then complete mineralization of fragmented compounds by microbial activity, which produces carbon dioxide, water, ammonium, or micro-organisms (Khalid & Arif, 2022). There are four steps in biopolymer degradation: biodeterioration, depolymerization, bio-assimilation, and mineralization, as illustrated in Fig. 2. In biodeterioration, biopolymeric materials are converted into small fragments due to the development of the microbial film. Micro-organisms of biofilm secrete extracellular enzymes, which promote the depolymerization of polymer networks into monomers, dimers, or oligomers. The primary and secondary metabolites in the bio-assimilation process are produced due to the uptake of small molecules into microbial cells (Nikolaivits et al., 2021). Finally, mineralization of these metabolites occurs and results in the formation of end products, including CH_4 , CO_2 , N_2 , and H_2O , and released into the atmosphere (Goel et al., 2021).

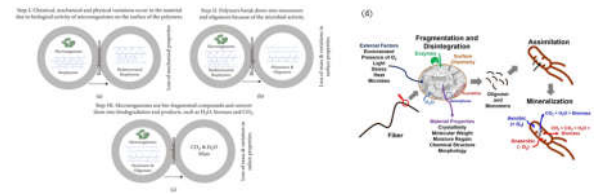


Figure 2: (a) Biodeterioration, (b) biofragmentation, (c) assimilation are the three major steps which describe the c, and (d) mechanism of biodegradation of polymer (Zambrano et al., 2020 & Din et al., 2022).

B. Renewable Sources

Derived from renewable resources such as plants or agricultural waste, reducing dependency on finite fossil fuels. Green composites represent a significant advancement in material technology by utilizing renewable resources, reducing carbon footprints, and promoting sustainable waste management. Their benefits over conventional materials are clear as they support environmental stewardship, offer efficient resource use, and align with consumer preferences for eco-friendly products (Khalid & Arif, 2022).

C. Reduced Environmental Impact

The production of green composites typically emits lower greenhouse gases and consumes less energy than conventional plastics. They are less likely to contribute to pollution due to minimized waste production and lower environmental toxicity

and can be sustainably managed. Leveraging renewable resources and promoting sustainable practices, green composites contribute to a more eco-friendly and resilient future, aligning with global efforts to combat climate change and preserve the natural ecosystem (Khalid & Arif, 2022).

IV. DRAWBACKS OF GREEN COMPOSITES

Despite their promising benefits, green composites face challenges and limitations that affect their widespread adaptation in food packaging:

A. Mechanical Strength

Green composite gives a less comparable strength to conventional plastics, especially for applications requiring high durability and impact resistance. Packaging materials require excellent tensile properties and permeability (Khalid & Arif, 2022). Zampaloni et al. (2007) used random-orientated hemp, flax, knaf, sisal, and coir fibre/polypropylene to prepare a composite via compression molding. The result suggests that 40% by weight hemp fibre composition exhibited a higher tensile and flexural strength than 40% by weight kenaf, flax, coir, or sisal fibre composites. High tensile strength is achieved when reinforced with strong natural fibres like flax or hemp. In another work, Biwas et al. (2011) applied hand lay-up to randomly oriented coir fibre/epoxy composite. The outcome revealed that fibre length of 30 cm was optimum to achieve maximum tensile and flexural strength. An increase in fibre length increased the impact resistance of the composite. The flexural strength performance and stiffness of a green composite vary depending on the type of natural fibre used and the matrix material (Joseph et al., 2002).

B. Cost Effect

Production costs of green composites can be higher due to the extraction and processing of natural fibres or bio-based polymers. The price of both the raw material and its processing cost can fluctuate based on supply and demand, impacting overall production cost. Developing green composite materials often involves substantial research and development expenses which include testing, validation and refining the materials to meet performance and safety standards.

C. Scalability

Industrial-scale production and processing of green composites may require significant infrastructure, investments, and technological advancements. Green composite often relies on renewable or bio-based materials, which can be less consistent in quality and availability than traditional materials. Ensuring a stable and sufficient supply of these materials at scale is crucial for maintaining product quality and cost-effectiveness. Moreover, scaling up production may require the adaptation or redesign of manufacturing processes to accommodate the specific properties of green composites which involve significant investment in new equipment or modifications to existing machineries.

D. Regulatory Approval

Meeting stringent regulatory standards for food contact materials and ensuring product safety can pose challenges, requiring extensive testing and certification processes. These comprehensive tests and documentation are required to comply with food safety regulations, which can be time-consuming and costly.

V. NANOSTRUCTURES IN COMPOSITE FILMS

Nanostructures in composite films refer to the deliberate arrangement of materials on a nanoscale, typically between 1-100 nm, to create unique properties and enhance performance (Rao and Vakkalagadda, 2023). By incorporating nanoparticles, nanofibers, nanolayers, or nanocrystals into a film matrix, researchers can engineer composites with improved mechanical strength, thermal and electrical conductivity, optical properties, and barrier functions. These nanostructured composites have far-reaching applications, including advanced packaging materials, corrosion-resistant coatings, biomedical devices, energy storage systems, and water treatment membranes. By tailoring the nanostructure design and material selection, scientists can unlock new functionalities and create innovative solutions for various industries, making nanostructured composite films a vibrant area of research and development.

A. Types of Nanostructures

Nanostructures significantly enhance composite film performance, offering versatility and efficiency. Types include nanoparticles, nanofibers, nanotubes, nano-layers and nano-composites. These nanostructures improve mechanical strength, thermal stability, optical properties, electrical conductivity, and barrier properties. Applications span packaging, energy storage, biomedical devices, optoelectronics and water treatment (Nasrallahzadeh et al., 2019).

B. Nanoparticles

Nanoparticles such as silver nanoparticles, and titanium dioxide nanoparticles, are widely used for their antimicrobial, UV -UV-blocking, and barrier enhancement properties. They are dispersed within the polymer matrix to impart specific functionalities without compromising film transparency or flexibility. Silver nanoparticles themselves are not considered natural; they are engineered materials created through various manufacturing processes. However, silver has been used historically for its natural antimicrobial properties. In nature, silver ions and compounds have been known to exhibit antimicrobial effects, which is why silver nanoparticles are used in packaging to leverage these properties in a controlled, efficient manner (Nasrollahzadeh et al., 2019). Silver nanoparticles (AgNPs) are extensively utilized in food packaging due to their robust antibacterial properties. AgNP-integrated packaging has been tested for diverse food products, including fresh fruits, meats and consumer goods. However, concerns arise regarding potential health risks from AgNP or silver ion migration into food. Consequently, food safety regulators have established guidelines governing AgNP use in

food packaging to mitigate potential risks (Istiqola et al., 2020).

C. Nanofibers

Nanofibers are ultra-fine fibers with diameters measured in nanometers (1-100 nm). They exhibit unique properties due to their small size, large surface area and high aspect ratio (Altaf et al., 2020; Xue et al., 2017). Electrospun nanofibers typically possess solid structures. However, introducing pores enhances the specific surface area. Two approaches achieve porous nanofibers: (1) selective component removal and (2) rapid cooling-induced polymer-solvent phase separation. Our research successfully employs both methods. For instance, porous ceramic nanofibers are fabricated via electrospinning composite solutions, followed by polymer removal through calcination (Li et al., 2005; McCann et al., 2005; Xie et al., 2005; Lu & Xia, 2013; McCann *et al.*, 2006). Electrospun nanofibers, typically composed of polymers like polyvinyl alcohol (PVA) or polylactic acid (PLA), provide a high surface area-to-volume ratio and mechanical strength. These nanofibers enhanced the mechanical integrity and barrier properties of the composite films, making them suitable for food packaging and biomedical applications (Nasrollahzadeh et al., 2019).

D. Nano-clays

Nano-clays are layered mineral silicate nanoparticles categorized into montmorillonite, bentonite, kaolinite, hectorite and halloysite based on chemical composition and structure. They exhibit high surface areas, versatility, and unique properties. Applications include polymer nanocomposites, cosmetics, pharmaceuticals, water treatment and catalysis. Characterized by softness, swelling capacity and ceramic suitability, nano-clays' specific characteristics vary among types. Their nanoscale dimensions and layered silicate structure enable diverse uses, making them valuable materials in various industries (Gupta and Roy, 2020). Montmorillonite and other layered silicate nano-clays are popular additives in composite films due to their excellent barrier properties against gases like oxygen and carbon dioxide, which also enhance mechanical strength. These nano-clays are dispersed in the polymer matrix to create a tortuous path for gas molecules, significantly improving the film's gas barrier performance (Nasrollahzadeh et al., 2019).

VI. METHODS OF INCORPORATION OF NANOSTRUCTURES

Various techniques are employed to integrate nanostructures into composite films:

A. Solution Casting

Nanostructures are dispersed in a solvent along with the polymer resin, followed by casting and evaporation of the solvent. This method ensures uniform distribution of nanoparticles or nanoclays within the film matrix. The solution casting method is the most common wet process for producing nanocellulose-based films. It involves mixing nanocellulose and polymer solutions, removing solvents through drying or

evaporation and casting the remainder onto a plate (Figure 4a). This method yields two categories: aqueous and non-aqueous suspensions. Aqueous suspensions easily disperse nanocellulose for stable, film-forming mixtures. Non-aqueous suspensions require modification treatments (alkylation, acetylation, esterification, TEMPO oxidation, polymer grafting or physical adsorption) for uniform dispersion. Kang et al. (2021) demonstrated this method's effectiveness by incorporating natural antioxidants into gum arabic-cellulose nanocrystal composite films, extending raspberry preservation time.

B. Melt Mixing

In this method, nanoparticles or nanofibers are directly mixed with the molten polymer during extrusion or injection moulding processes. Melt mixing facilitates the homogeneous dispersion of nanostructures and is suitable for the large-scale production of composite films. Melt processing involves melting polymers at high temperatures and solidifying them into desired shapes via cooling. Techniques include extrusion, blow molding and injection molding (Abdallah et al., 2022). Extrusion is commonly used for food packaging films due to high production efficiency and mass production suitability. However, nanocellulose's hydrophilicity and susceptibility to degradation under extrusion's high temperature (200-300°C), pressure and shear stress pose challenges. To overcome this, modified treatments ensure dispersion, and strict temperature control prevents decomposition, enabling successful development of nanocellulose composite films (Chen et al., 2011).

C. Electrospinning

Electrospinning produces nanofiber membranes by dissolving polymers in organic solvents and applying high-voltage electric fields to generate strong charges and increase surface energy. The solution is then stretched, polarized and deposited onto a flat plate, forming closely stacked films with diameters ranging from 2 nm to several micrometers (Mirjalili & Zohoori, 2016). This method offers high porosity, specific surface area, material versatility and non-thermal processing, making it suitable for food packaging films (Abdallah et al., 2022)57]. For instance, Park et al. (2019) electrospun poly(vinyl alcohol)/cellulose nanocrystal composites (50 µm thickness), resulting in 83% and 52.3% increases in elastic modulus and tensile strength, respectively, compared to neat poly(vinyl alcohol) films (Mirjalili et al., 2016).

D. Layer-by-Layer Assembly

This technique involves alternating deposition of polymer and nanoparticle layers to build up a composite film with controlled thickness and functionality. Layer-by-layer (LBL) assembly allows precise tuning of film properties, such as permeability and surface chemistry, for specific applications. The LBL technique deposits alternating layers of oppositely charged materials on a substrate, forming uniform multilayer films. This method enhances film properties by incorporating nanomaterials, biological macromolecules and conductive polymers, making it suitable for composite

materials. However, its industrial applications are limited due to slow processing and suitability only for small samples. Notably, Ogonsona et al. (2020) used hydrogen bonding between cellulose nanocrystals and polyvinyl alcohol to create composite films, achieving 415% strength, 2300% modulus increases and complete oxygen permeation blockage when cellulose nanocrystal content reached 10% (Silva et al., 2020).

E. Sol-Gel Process

This technique involves the hydrolysis and condensation of metal alkoxides in the presence of a polymer matrix (Silvia et al., 2023). Nanostructures are formed within the gel network, which is then processed into a composite film. Sol-gel processing allows for precise control over nanoparticle size and distribution, enhancing film properties such as optical transparency and mechanical strength.

F. Spray Coating and Dip Coating

Nanostructures can be deposited onto substrates via spray coating or dip coating methods. In spray coating, nanoparticles or nanofibers dispersed in a liquid medium are sprayed onto the substrate to form a thin film while dip coating involves immersing the substrate into a nanoparticle suspension followed by withdrawal to coat the surface evenly (Raji et al., 2021a and Raji et al., 2021; Hongzhi et al., 2023). These methods are suitable for applying functional coatings to complex-shaped objects for producing thin films with controlled nanoparticle density. Nanocellulose composites form edible coating films that enhance food preservation by blocking gases, moisture, and grease, extending shelf life. In the food industry, these coatings prevent water loss, control respiration rates, regulate gas exchange, inhibit oxidative browning and maintain firmness. Applied via dipping, spraying, or brushing, they effectively preserve food quality. For instance, Pacaphol et al. (2019) coated spinach leaves with hemp-derived cellulose nanofibers (0.3-0.5% w/v concentration), demonstrating superior quality retention compared to uncoated spinach, showcasing their potential in food preservation (Xu et al., 2024).

G. In Situ Polymerization

Nanostructures can be synthesized directly within the polymer matrix through in situ polymerization processes. Monomers and nanoparticle precursors are polymerized simultaneously or sequentially to form a composite material with integrated nanostructures. In situ polymerization ensures strong interfacial bonding between nanoparticles and the polymer matrix, enhancing the mechanical and barrier properties of the composite film (Hongzhi et al., 2023).

VII. CHARACTERIZATION TECHNIQUES

Intercalated nanostructures, a rapidly emerging class of materials, have aroused great interest due to their many applications. Numerous techniques have been used to explain the size, crystal structure, elemental composition, and many other physical properties of nanoparticles (Venkatesan et al.,

2024b). A number of techniques can be used in different contexts to evaluate different physical attributes (Rashed et al., 2023). Among the methods that are frequently employed are X-ray diffraction analysis, microscopic techniques, thermal analysis (TA), spectroscopic techniques, and strength measurements (Mondal et al., 2023).

A. X-ray Diffraction

Solid identification and characterization have been greatly aided by X-ray diffraction (Mohammadkhani et al., 2024). An amorphous polymer's X-ray diffraction pattern won't have any sharp peaks, whereas nanocomposites' crystalline features cause them to have sharp peaks. The most popular applications of X-ray diffraction have been for routine characterisation and in-depth structural elucidation (Mughal et al., 2024). Understanding X-ray diffraction intensities is also crucial for obtaining precise structural information. The nanocomposites under investigation's phase and unit cell information are determined using powder X-ray diffraction (XRD) (Dinesha et al., 2023). Scherrer's formula is another often-used technique in particle size determination. The well-known Debye-Scherrer Eqn. 1 is used to calculate the sizes of nanoparticles and nanocomposite materials (Rashed et al., 2023).

$$D = K\lambda / \beta \cos\theta \quad (1)$$

where D is the crystallite size, K is the shape factor, calculated for a spherical is 0.9, and β is full width at half maxima of the highest peak in radian.

However, from the work of Mohammadkhani et al (2024). It can be observed that these outcomes validate ZnP-PVA's effective synthesis. Furthermore, the complex's crystalline nature is demonstrated by the composite's strong peaks (Fig. 3). ZnP-PVA/CMC X-ray diffraction patterns display the distinctive PVA and zinc phosphate peaks. Moreover, the two faint new peaks at $2\theta = 13.76^\circ$ and 20.87° show that CMC has both a crystalline and an amorphous structure.

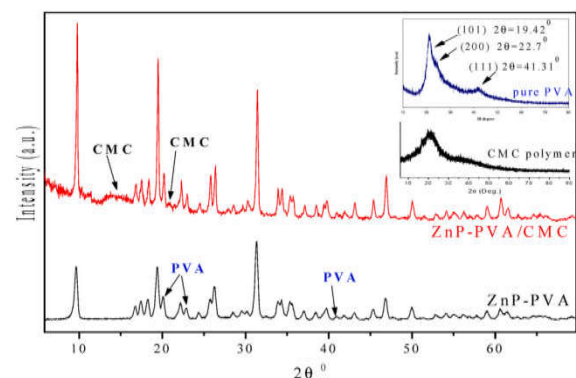


Figure 3: X-ray diffraction (XRD) patterns for zinc phosphate/polyvinyl alcohol, carboxymethyl cellulose, polyvinyl alcohol, and zinc phosphate/polyvinyl alcohol (Mohammadkhani et al., 2024).

B. Thermal Analysis

To ascertain the stability of nanocomposite materials and various phenomena resulting from doping, curing, and annealing, thermal analysis, including thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), dynamic mechanical thermal analysis (DMTA), thermal mechanical analysis (TMA), etc.—is a useful tool (Mughal et al., 2024). The typical information provided by the thermal analysis technique includes the processes leading to the thermal decomposition of the nanocomposites, the endothermal or exothermic character of the decomposition process, solvent/moisture loss, weight loss at each step, final degraded materials, etc (Thirugnanasambandan & Gopinath, 2023).

For instance, Venkatesan et al. (2024b) in their work suggest that the PBAT and PBAT-GA/CNPs nanocomposites' TGA curves at various CNP concentrations (Fig. 4). A list of thermal characteristics is given in Table 1. Due to a PBAT breakdown, a weight decrease was seen at 300 and 350 °C. When the temperature surpassed 350 °C, PBAT deterioration was the main cause of the weight loss. Low thermal stability was observed in the PBAT-GA without CNPs.

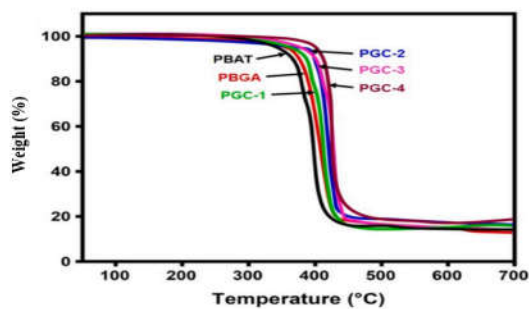


Figure 4: TGA curve of the PBA-GA/CNPs nanocomposite (Venkatesan et al., 2024b)

Table 1: TGA results of nanocomposite of PBAT, TA, and CNPs

| SNO | Samples | TGA | | |
|-----|---------|--------------------------------------|------------------------------------|------------------|
| | | Initial degradation temperature (°C) | Final degradation temperature (°C) | Ash content (°C) |
| 1. | PBAT | 329.3 | 456.8 | 3.87 |
| 2. | PBGA | 332.1 | 460.4 | 2.94 |
| 3. | PGC-1 | 354.5 | 466.9 | 2.59 |
| 4. | PGC-2 | 387.9 | 471.5 | 2.01 |
| 5. | PGC-3 | 408.4 | 480.0 | 1.54 |
| 6. | PGC-4 | 415.6 | 492.3 | 2.66 |

C. Fourier Transforms Infrared Spectroscopy (FTIR)

Fourier transform infrared (FTIR) spectroscopy can be used to determine any potential physicochemical interactions between the filler and the matrix. The polymer

matrix's vibrational frequencies shift to a lower frequency upon the addition of nanofillers (Chen et al., 2023). Additionally, the presence of functional group vibration bands in manufactured materials was quantified using FTIR analysis. Furthermore, The example of FTIR from the work of (Sharif & Tavakoli, 2023), can be observed from The FTIR spectra of the composites made of epoxy/chitosan-GO, GO, chitosan, and GO displayed in the figure. Two peaks related to functional groups were identified in the chitosan spectrum: The N-H bending vibration of NH₂ and the C-O stretching vibration of NHCO appear at 1651 and 1596 cm⁻¹, respectively. An absorption band is also visible in the OH bands at 3400 cm⁻¹, while the NH₂ groups exhibit two bands at 3295 and 3365 cm⁻¹ (Shan et al., 2023). The peak in the chitosan-GO composite spectrum is located at 1645 cm⁻¹ as indicated in Fig.5, which can be attributed to the combined action of both hydrogen bonding between polycationic CS and the negative charge of GO, as well as between CS and the oxygenation groups in GO (Schwartz -Narbonne et al., 2023).

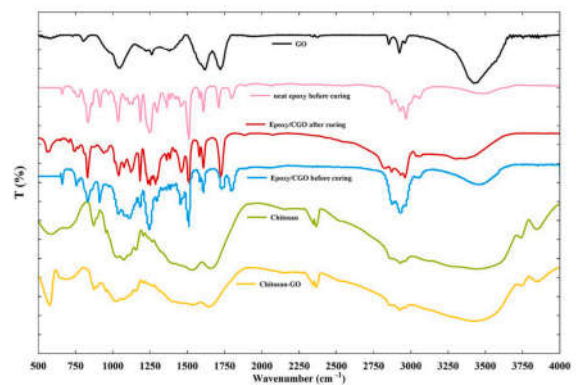


Figure 5: FTIR spectra Chitosan, chitosan-GO, and epoxy/chitosan-GO (Schwartz -Narbonne et al., 2023).

D. Transmission Electron Microscopy (TEM)

In its most basic bright-field mode, TEM is frequently used as a technique for direct viewing of PNCs' nanocomposite structure. This is made possible by the fact that the polymer matrix and most of the filler—inorganic elements like metal oxides—have enough contrast for the electrons that are transported. In the worst situation, a qualitative image of the inorganic filler crystal structure can even be obtained using high-resolution TEM (Jahura et al., 2023). It is commonly known that only a small portion of the material is needed to produce a transmission electron micrograph, and the final product might not be entirely representative (Chen et al., 2023).

Sasirekha et al., 2023 used surfactant-assisted sol-gel to create CuO/TiO₂ nanocomposites at room temperature. In the work, the agglomeration of CuO/TiO₂ nanocomposites was reduced using a surfactant such as hexadecyltrimethylammonium bromide in the sol-gel process. SEM (scanning electron microscopy) using a tabletop Hitachi 3000 was used to analyse the morphology. The product's nanostructure was examined using transmission electron microscopy (TEM). To prepare samples for TEM, 2-propanol

metal oxide nanoparticle dispersion was dropped onto a holey carbon grid, and the grids were vacuum-dried for a full day (Fig.6b).

E. Scanning Electron Microscopy (SEM)

SEM is a valuable method for producing a visual representation of materials at the micron and, in certain situations, submicron resolution levels. The great resolution that may be achieved with SEM is one of its main benefits. The specimen seems three-dimensional in SEM photos, which is another feature. As a result, SEM is especially useful for describing the specimen's crystallographic, magnetic, and electrical properties as well as for figuring out whether the presence of other molecules on the specimen surface has changed the morphology of the particles (Jahura et al., 2023). When small amounts of nanoparticles are introduced to the polymer—polymeric chains cover the nanoparticle—SEM is used to ascertain the morphology and shape of the material's surface in a polymer matrix nanocomposite. As a result, nanoparticles in the matrix cannot be identified in a SEM surface picture (Fig. 6a).

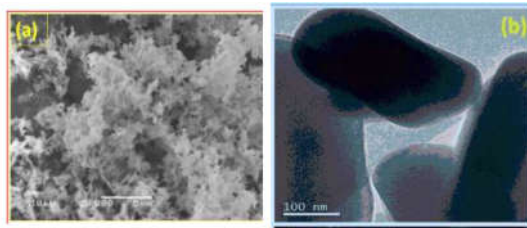


Figure 6: CuO/TiO₂ nanocomposite prepared by surfactant-assisted sol-gel method (a) SEM image (Jahura et al., 2023), (b) TEM image (Sasirekha et al., 2023).

VIII. PERFORMANCE METRICS

A. Tensile Strength

Before testing, the tensile specimen was conditioned for 48 ± 2 hours at 37°C . The specimens were each fastened individually in a vice that clamps into a universal testing apparatus that has a 50 mm/min crosshead speed and a 5 kN load cell. Newtons (N) were used to record the failure load. The following Eqn. 2 was used to determine the tensile strength value (Nizaro et al., 2024):

$$T_s = F/A \quad (2)$$

where A is the area of a cross-section at failure (mm^2), F is the load at failure (N), and TS is the tensile strength (N/mm^2).

Nizaro et al., 2024 presented and examined the impact of different CMC concentrations on PVA/CMC/CNF nanocomposites, using a PVA/CMC and CNF ratio of 80:20 and 90:10, respectively. The physical and tensile characteristics of the nanocomposites were evaluated because they may have an impact on the coating's performance. Additionally, paper was used for the coating process, and the coated paper's performance was examined. As the CMC concentration increased, the viscosity increased as well, and

the zeta potential was good, indicating good dispersion, according to the results. The PVA/CMC/CNF nanocomposites' tensile qualities were enhanced by the inclusion of CMC. However, agglomeration was discovered during SEM analysis of PVA/CMC-1: CNF (80:20), which could have an impact on the coated paper's performance. It's interesting to note that PVA/CMC-1: CNF (80:20) had the lowest Cobb60 and outstanding water resistance. Furthermore, WVTR increased with the addition of 1 weight percent CMC, but it stayed lower than the blank sample. In contrast, PVA/CMC-2: CNF (80:20) performed the best in the tests of ripping resistance and oil absorption. In conclusion, the physical and tensile qualities of PVA/CMC/CNF, as well as the rip strength and barrier qualities of the PVA/CMC/CNF coated paper, may all be successfully enhanced by the addition of CMC.

Barrier Properties

Packaging is much more than just product promotion or ease of transportation. Packing is essential for protecting goods and guaranteeing their integrity and quality. However, comprehending the idea of barrier materials is necessary to grasp how various packaging materials fit into this process (Sankarganesh et al., 2024). The inherent qualities of packing materials that regulate the flow of gases, moisture, light, and microbes are referred to as barrier properties. To what extent are they airtight or light-reflective? Do they possess antibacterial qualities? Do they withstand moisture? It is crucial for many businesses, including electronics, food & beverage, pharmaceuticals, and more, to comprehend these qualities. Certain items work better with certain kinds of packing materials to preserve their effectiveness, freshness, and usability. Therefore, it is critical to select appropriate primary and secondary packing options in order to preserve product integrity (Ghosh et al., 2024). Barrier can be also classified into the following:

Gas barrier: In packaging, the capacity to regulate gas permeation, particularly oxygen is essential. Oxygen can change the chemical makeup of different things, speed up spoiling, and break down delicate substances. For this reason, materials with strong gas barrier qualities are essential for maintaining freshness and increasing shelf life.

Barrier against Moisture: Many products are seriously threatened by moisture intrusion, which can lead to deterioration, the formation of mould, or changes in physical characteristics. To preserve durability and prevent deterioration, medications, electronics, and some food items require effective moisture barriers.

Light-Resisting Barrier: Light exposure, especially UV and visible light can cause photosensitive materials to deteriorate. Sufficient light barriers in packaging materials guard against this kind of deterioration, maintaining the integrity and stability of the contents inside.

Microbiological Barrier: Strong microbial barrier materials are essential in businesses where sterility and the avoidance of microbiological contamination are required. To

guarantee product safety, pharmaceuticals, medical equipment, and specific food items depend on these kinds of barriers.

Nanocomposites improve the barrier qualities by allowing gases to escape through a convoluted path. Reduced permeability to gases causes oxidation to be delayed and increases shelf life. Their inherent structure causes gasses and tiny chemicals to permeate (Momtaz et al., 2024). Nevertheless, the barrier qualities of biodegradable polymers are improved when they are reinforced with nanoparticles or nanofillers. Nanocomposites improve the barrier qualities by allowing gases to escape through a curved channel. Reduced gas permeability delays oxidation and increases shelf life (Dong et al., 2024).

E. Previous Studies on Biodegradation Based on Composite Materials

Jamwal & Mittal, 2024 carried out the casting of two cassava starch-based film layers together. A biodegradable and active bilayer nanocomposite (TPS-Y/NP) is created that may be used as packaging to increase the shelf life of food. A starch-yerba mate extract film (TPS-Y) and a starch-titanium dioxide nanoparticles nanocomposite (TPS-NP) make up the first layer. Excellent interlayer compatibility is achieved in both films when the same starch matrix (TPS) is used. Because of the contribution of the nanocomposite layer, the bilayer exhibits activity against several pathogens, increases in mechanical resistance, and increased water vapour permeability (WVP). Additionally, the layer containing the natural extract exhibits antioxidant activity and greater deformation. Furthermore, in just two weeks, all films nearly entirely decompose in vegetable compost. With its antioxidant and antibacterial properties, this bilayer film holds great potential as a biodegradable and functional food packaging material.

In another study, the experimental and theoretical investigation on structure, toxicity, and DNA interaction of turmeric-coated cobalt ferrite nanocomposites. The structure, toxicity, and DNA interaction of the co-precipitated turmeric at CoFe_2O_4 nanoparticles (NPs) were thoroughly examined. As a novel technique to confirm the interaction between the surface of NPs and the turmeric biomolecules, the magnetic hysteresis loop of the nanocomposite. The results of the experiment show that the viscosity of the calf thymus-DNA (CT-DNA) increased significantly, as demonstrated by the data. Additionally, it was determined using fluorometric analyses using methylene blue and Hoechst 33,258 as fluorescence probes that the NPs bonded to CT-DNA interactive. Based on the temperature dependence results, the thermodynamic parameters ($\Delta H^\circ > 0$ and $\Delta S^\circ > 0$) indicated that hydrophobic forces were mostly responsible for the coated NPs' binding to CT-DNA which was simulated using the Monte Carlo method in addition to the FT-IR and TGA studies, where the biocompatible nanocomposite is considerable in the field of medicine (Mirzaee et al., 2024).

Bhat et al., 2024 used chitosan/poly-vinyl alcohol-based active films loaded with white turmeric powder for food

packaging applications. The purpose of this work is to create and evaluate antibacterial films for food packaging applications using chitosan (CS) and polyvinyl alcohol (PVA) combined with white turmeric powder (WT). Solvent casting was used to create the active films of chitosan/cetrimide/white turmeric (CCW), poly-vinyl alcohol/cetrimide/white turmeric (PCW), and PVA/CS/CT/WT (PCCW) with different concentrations of white turmeric (WT). The results of the study showed that an increase in white turmeric (WT) content improved the tensile strength, moisture adsorption, solubility, and hydrophobicity of CCW active films.

Ragab et al., 2024 also investigated the improved optical, thermal, mechanical, and electrical properties and antibacterial activity of PVA-chitosan by biosynthesized silver (Ag) nanoparticles: Eco-friendly nanocomposites for food packaging applications. In this study, polyvinyl alcohol (PVA) and chitosan (Cs) polymers were blended, with 70% PVA and 30% Cs to create nanocomposite films. Silver nanoparticles (Ag NPs) were then added using a solution-casting technique. The purpose of the study is to examine how *Chenopodium murale* leaf extract-biosynthesized Ag NPs affect optical. The results of the findings revealed that with the addition of Ag NPs, XRD examination revealed a decrease in the degree of crystallinity. Ag NPs were detected by TEM to have an average size of 23.4 nm and to be spherical and cubic in shape. Changes in surface morphology were revealed by SEM and AFM. Ag ions and the mixture interacted, as evidenced by FT-IR spectra. When the concentration of Ag NPs increased, the energy gap shrank. The TGA demonstrated improved thermal stability. Mechanical qualities are much improved.

Preparation of transparent and flexible regenerated kenaf CNF composite films with curcumin-metal complex for food packaging applications was carried out. Regenerated composite films were created by combining curcumin (Cur)-metal complexes with cellulose nanofibers (CNF) sourced from the Kenaf plant. Homoleptic Cur-metal complexes including paramagnetic Cu(II) and diamagnetic Zn(II) metal ions were created using cur. Cur-Zn(II) complex and Cur-Cu(II) complex were synthesised using identical reaction conditions to examine the synergistic effect of forming strong coordination bonds with two distinct metal ions to engage Cur's diketone electrons. The Cur-Zn(II) complex-loaded CNF composite films demonstrated significant antibacterial activity against foodborne pathogenic bacteria like *Escherichia coli* and *Listeria monocytogenes*, while the Cur-Cu(II) complex-loaded CNF composite films demonstrated higher antioxidant activity than other films. The antioxidant and antibacterial qualities of Cur are a result of the coordination of its diketone electron with paramagnetic and diamagnetic metal ions. This study demonstrated that Cur may be used for active food packaging applications in the form of Cur-Zn(II) complex as an antioxidant filler and Cur-Cu(II) complex as an antibacterial filler (Kumar et al., 2024).

Wen et al., 2023, in their work, turmeric carbon quantum dots enhanced chitosan nanocomposite films based on photodynamic inactivation technology for antibacterial food packaging was studied. To create a series of active

composite food packaging films (CDs-CS), we coupled the photodynamic inactivation of antibacterial technology in food packaging materials with fluorescent carbon quantum dots (CDs) made from natural plant turmeric into a chitosan matrix. The CD-containing chitosan film was more hydrophobic, had superior mechanical qualities, and provided UV protection. However, the composite film was able to generate a large amount of reactive oxygen species when exposed to a 405 nm light source, and the CDs-CS2 film showed decreases in *Staphylococcus aureus* and *Escherichia coli* of about 3.19 and 2.05 Log₁₀ CFU/ mL, respectively, within 40 minutes. In applications involving cold hog storage, CDs-CS2 films demonstrated a reduction in the development of colonization in swine and a ten-day delay in the meat's deterioration. This research will offer fresh perspectives on the investigation of effective and safe antimicrobial food packaging.

For instance, it's crucial to contrast certain features of turmeric oil-intercalated nanocomposites with more sophisticated packaging technologies as well as more conventional food packaging solutions when evaluating these materials for food packaging. This is a comparative study that emphasizes important elements. This review considers traditional and advanced technology in terms of the material used and its functions.

Biodegradable PBAT/PLA blend films incorporated with turmeric and Cinnamomum powder. A flat extrusion process was used to create biodegradable films based on a polymer blend called PBAT/PLA. Five-weight percent of powdered cinnamon or turmeric was used during the preparation of the films as a natural addition (de Castro et al., 2024). Colourimetric, UV light transmittance, water contact angle, water vapour permeability, shape, mechanical properties, and antioxidant activity were all used to analyse the resulting films as well as those that underwent two rounds of reprocessing. Cinnamon increases a surface's hydrophobicity and decreases its absorbance of UV radiation. The morphological examination showed that reprocessing resulted in higher dispersion and distribution along with larger elongation and maximum load. The films created, with a focus on cinnamon-additive films, offer a great deal of promise for use in active food packaging.

In another study, the fabrication of chitosan-based food packaging film impregnated with turmeric essential oil (TEO)-loaded magnetic-silica nanocomposites for surimi preservation. To create core-shell nanocomposites, porous silica (Si) was used to cap the core magnetic nanoparticles (MNPs). Turmeric essential oil (TEO) was then loaded into these nanocomposites with an encapsulation effectiveness of 75.24%. To create an active bio nanocomposite film, the synthesized nanocomposite was mixed with chitosan (CS) and evaluated for effective bio nanocomposite impregnation. After adding MNPs/Si/TEO nanocomposite, the film's mechanical and physical qualities were considerably enhanced. After six days of storage, uncontrolled turmeric essential oil (TEO) release from chitosan (CS) film led to bacterial growth, but bio nanocomposites showed a continuous release of TEO that

reduced the microbial burden from 4.0 log CFU/g to 2.78 log CFU/g over a 14-day period (Surendhiran et al., 2022).

Previous Studies on the Antibacterial and Antioxidant Properties of Nanocomposite Films

Zagloul et al., 2024 investigated a multifunctional Ag₂O/chitosan nanocomposite synthesized via sol-gel with enhanced antimicrobial, and antioxidant properties as a novel food packaging material. The study synthesized nanocomposite films utilizing chitosan (CS) as the base material and various weight percentages of silver oxide nanoparticles (Ag₂O) (5 %, 10%, and 15% Ag₂O/CS) using a one-step in situ sol-gel process. Several analytical approaches were used to study the structural properties of Ag₂O/CS films. The nanocomposite films were tested against Gram-positive (*Bacillus subtilis*, *Enterococcus faecalis*, and *Staphylococcus aureus*) and Gram-negative (*Escherichia coli* and *Pseudomonas aeruginosa*) bacteria, the synthesized Ag₂O/CS nanocomposite shown encouraging antibacterial activity. Additionally, the Ag₂O/CS nanocomposite showed strong antifungal activity against *Penicillium chrysogenum*, *Aspergillus flavus*, *A. fumigatus*, *A. niger*, and *Candida albicans*. By using ABTS radical scavenging, the antioxidant activity of the created nanocomposite films was investigated. Achieving the maximum levels of antioxidant and antibacterial activities involved adding 15% of silver oxide to the chitosan.

Biodegradable cellulose/curcumin films with Janus structure for food packaging and freshness monitoring were also conducted (Wang et al., 2024). Based on the pH-driven principle of curcumin, regenerated cellulose/curcumin composite films were created by uniformly dispersing hydrophobic curcumin in a hydrophilic cellulose matrix using an aqueous alkali/urea solvent. To create the Janus structure, a unilateral hydrophobic alteration was also performed using chemical vapour deposition of methyl-trichlorosilane. The developed film demonstrated that fish held in storage could have their overall levels of volatile basic nitrogen decreased. The colour of the films turned from pale yellow to reddish-brown during storage.

In another work, Korumilli et al. (2024), 22 – Nano-clay-reinforced bio-composites and their packaging applications were investigated. Packaging-related nano-clay-reinforced bio-composites: characterization methods, performance assessment, and prospects for the future. These novel composites strengthen mechanical properties and environmental sustainability by combining biodegradable polymers with nano-clay particles. The bio-composites that are produced have increased modulus, tensile strength, and thermal stability, making them desirable materials for packaging. A wide range of variables is considered in the assessment of performance, such as mechanical characteristics, barrier qualities, thermal stability, biodegradability, food compatibility, ageing, dispersion of nano-clay, microbial degradation, recycling feasibility, and cost-effectiveness.

IX. PROSPECTS AND CHALLENGES

A. Innovations and Trends

The developed nanostructures have been used in numerous applications, including mirror housings on different makes and models of vehicles, door handles, door panels, instrument panels, trunk liners, parcel shelves, headrests, roofs, upholstery, engine covers, intake manifolds, and timing belt covers. Additional applications under consideration are vacuum cleaner impellers and blades, power tool housings, mower hoods, and covers for portable electronic devices like cell phones and pagers, among others (Singh, 2019; Singh et al., 2021; Sachdeva et al., 2021).

B. Market Potential

Commercial clay-nylon-6 nanocomposite materials were created by Honeywell for use in drink containers. A mixture of thermoplastic starch (TPS) serves as the basis for Starch Based Resin 11C, a biodegradable and compostable resin (Singh, 2019). The main uses of the starch-based resin 11C are in the production of produce and meat liners (overwrap packaging, mulch film, breathable film), as well as compostable bags (shopping bags/checkout bags, green bin liners) (Singh, 2019; Dybka-Stepien et al., 2021).

C. Regulatory and Consumer Acceptance

Even though nanotechnology is the subject of several studies, the advantages of naturally occurring nanosystems and their functions have not received enough scientific investigation. Before being permitted to be sold, foods that have undergone nanotechnology must undergo mandatory testing. To determine the risk of human exposure to nanoparticles (NPs), it is necessary to conduct standardized tests on living cells. Also, Due to inconsistent data reporting and a lack of established test methodologies, the toxicology of nanoparticles is poorly known. The incorrect characterization of NPs and the interferences that the NPs in the assay equipment caused are the causes of the inconsistency in the published findings (Kroll et al., 2008). Therefore, guidelines for safe usage, proven processes, and NP disposal should be provided by regulatory authorities and policymakers.

X. CONCLUSION

Ultimately, our study's goal was to compile technological innovations and advancements for creating green intercalated nanostructure. Using natural fibre as the matrix, natural fibre-reinforced composites are found to be the most environmentally friendly materials during the investigation. Because of this, several intriguing green nanocomposites with qualities like tensile strength, barrier properties and biodegradability have been discovered through a variety of research projects, including those involving thermoplastic starch and its blends, PLA and its modifications, cellulose, gelatine, chitosan, etc. Aside from being preferred for environmental reasons over synthetic fibres, natural fibre can also be produced synthetically from agricultural sources such as sisal, kenaf, jute, hemp, flax, bananas, bamboo, and coconut coir. Thus, nanocomposites have a wide range of potential

uses. More research is being done on developing efficient delivery systems to improve nutrient absorption. The creation of nano-sensors that may be included in packaging materials to check food quality continuously is a growing trend. Nano-sensors can provide valuable information about food goods, including freshness, spoilage, and contamination. Nanostructured materials can enable personalized nutrition by delivering nutrients based on an individual's needs. Research looks into how nanotechnology might be used to customize diets and improve health results. These case studies demonstrate the potential advantages and uses of turmeric oil and similar substances in food packaging, especially when combined with nanocomposites. Turmeric oil can boost mechanical and barrier performance, increase antibacterial and antioxidant qualities, and provide environmentally friendly substitutes for conventional packaging materials in nanocomposites. Although there aren't many direct case studies that concentrate on turmeric oil-intercalated nanocomposites, the literature that is currently accessible demonstrates the viability and benefits of employing these materials in food packaging.

DECLARATION OF COMPETING INTEREST

The authors declare that they do not have any conflict of interest.

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