



Mangosteen Pericarp based Bionanohybrid Composites: A Comprehensive Review

Sherin G[#], Asha S Kumar^{*}, Sivakala S[^], Ambili Savithri^{\$}

[#] Research Scholar, Dept of Chemistry, Sree Narayana College, Chempazhanchy, Trivandrum, Kerala, INDIA

^{*} Associate Professor, Dept of Chemistry, Sree Narayana College, Chathannur, Kerala, INDIA

[^] Assistant Professor, Dept of Chemistry, Sree Narayana College, Chempazhanchy, Trivandrum, Kerala, INDIA

^{\$} Assistant Professor, Dept of Biochemistry, Sree Narayana College, Kollam, Kerala, INDIA

(Received: 16 January 2025

Revised: 20 February 2025

Accepted: 20 March 2025)

KEYWORDS

Mangosteen,
Bionanohybrid,
Biocomposites,
Biodegradability

ABSTRACT:

Introduction: In recent times, the overall demand for sustainable materials in place of low-cost, high-strength materials has been triggered worldwide, prompted researchers to develop eco-friendly biocomposites endowed with biodegradability, renewability and non-toxicity. Mangosteen pericarp based Nano hybrid biocomposites (MPNHBC) have gained more research focus in recently due to their promising properties. The present review encompasses progresses in the synthesis, properties and applications of bio composites giving special emphasis to MPNHBCs. The increasing demand for sustainable and eco-friendly materials has led to a surge in research on natural fiber-based composites. Mangosteen pericarp, a readily available and renewable resource, has emerged as a promising candidate for the development of biodegradable composites. Rich in cellulose, hemicellulose, and lignin, mangosteen pericarp offers a unique combination of mechanical, thermal, and chemical properties. This review aims to provide a comprehensive overview of the current state of knowledge on mangosteen pericarp-based composites, including their preparation, characterization, and potential applications. By highlighting the opportunities and challenges associated with these composites, this review seeks to stimulate further research and development in this exciting field.

Objectives: The objective of this review is to systematically summarize and critically evaluate the current state of knowledge on mangosteen pericarp-based composites, with a focus on their preparation, properties, and potential applications, in order to identify gaps, challenges, and future directions for research and development in this field.

Results: The results show that mangosteen pericarp-based composites exhibit promising physical and mechanical properties, thermal stability, and chemical resistance. Microstructural analysis reveals a unique composition and structure. These composites compare favourably to other natural fiber composites, with potential applications in packaging, biomedical devices, and construction materials. However, challenges remain, including scaling up production, improving standardization, and reducing costs. Addressing these challenges can help unlock the full potential of mangosteen pericarp-based composites.

Conclusions: Mangosteen pericarp-based composites have demonstrated tremendous potential as sustainable, biodegradable, and eco-friendly materials. The unique combination of mechanical, thermal, and chemical properties offered by mangosteen pericarp makes it an attractive candidate for various applications, including packaging, biomedical devices, and construction materials. While challenges related to scalability, standardization, and cost-effectiveness remain, ongoing research and development efforts are expected to address these limitations. As the world shifts towards a more circular and sustainable economy, mangosteen pericarp-based composites are poised to play a vital role in reducing our reliance on non-renewable resources and mitigating environmental impacts.



1. Introduction

Biocomposites are of great significance to the material world because they provide many unique properties of reduced environmental impact, lower carbon footprint, and enhanced sustainability. Also, their properties can be tailored based on discerning design composition and processing. This influences the use of biocomposites in different areas such as space, automotive, construction, and manufacture, marine, consumer products, electrical machineries etc. [1]. Biomass based composites are used in different areas such as furniture for garden and house, cars and technical devices also these materials are used in preparation of medicinal products and in nanotechnology. Researchers are developing these materials as alternatives to conventional materials that are non-renewable, and depleting. While mass scale production of biocomposites is becoming more cost-effective, the lasting nature of these natural materials limits their application in many environments. Efforts have been made to recycle, and convert value-added products from fruit peels, such as essential oils, food additives, dietary fibres, enzymes, polyphenolic compounds, biodegradable plastics, bio-ethanol, and pigments. *Garcinia mangostana* L. “The Queen Thai of fruit”, is the most popular fruit in Southeast Asia and distributed to others due to their tremendous flavour. The rind portion contains 4% total sugars, 1.4% fat, 1% protein, and 1.7% tannins. The rind has a high antioxidant potential and contains anthocyanin such as cyanidin-3-glucoside and cyanidin-3-sambubioside. Dried rind is also reported to possess antibacterial and antifungal activities. Some of the bioactive compounds such as garcinol and isogarcinol have been isolated from the fruit. [2] Mangosteen (*Garcinia mangostana*), a tropical fruit known for its health benefits, has a pericarp rich in bioactive compounds. Researchers have tapped into this resource to develop nano hybrid biocomposites that leverage the unique properties of mangosteen pericarp. These biocomposites exhibit excellent mechanical, thermal, and barrier properties, making them suitable for a wide range of applications. Mangosteen rind is generally used as a reinforcing bio-filler in polymer matrices. The investigation related to polymer composites reinforced with bio-fillers of mangosteen peel is limited. Some of the works shows the properties as an antibacterial and anticancer agent to develop wound dressing and food packaging from mangosteen

rind. Mangosteen peel is commonly used as a reinforcing bio-filler in polymer matrices and various studies show bio plastic composite using mangosteen peel as reinforcing filler in cellulose Nano crystal also reinforced in polymer. Mangosteen rind used as an antimicrobial filler in natural rubber for medicinal gloves, rubber transdermal patches, rubber toys, etc. exhibited a good look and noble mechanical properties. A number of daily domestic consumer stuffs such as furniture, automotive parts are made-up from biomass based composites using dispensation procedures such as compression moulding, injection moulding, and extrusion. The easy obtainability, non-abrasiveness, non-toxic nature, light mass of biomass centered material makes promising the development of new ecological things. The demand for sustainable products has seen a significant surge in recent years, driven by increasing consumer awareness and concerns about environmental sustainability. This trend is reflected in the growing demand for eco-friendly products, renewable energy sources, and sustainable materials. Several factors contribute to the increasing demand for sustainable products, including environmental concerns, government regulations, and social responsibility. Rising awareness about climate change, pollution, and waste management has led consumers to seek out sustainable products. Stricter environmental regulations and policies have also encouraged companies to adopt sustainable practices and develop eco-friendly products. [3] Furthermore, consumers are increasingly expecting companies to prioritize social responsibility and environmental sustainability, driving demand for sustainable products. The global demand for sustainable products has grown significantly over the past few years. According to recent surveys, sustainability is now one of the top three drives for consumer purchasing decisions in many countries around the world. Key statistics highlighting the growing demand for sustainable products include that 60% of consumers consider sustainability when making purchasing decisions and the global market for sustainable products is expected to continue growing driven by increasing consumer demand and government regulations. Overall, the demand for sustainable products is on the rise, driven by a combination of environmental concerns, government regulations, and social responsibility. As consumers continue to prioritize



sustainability, companies must adapt to meet this growing demand and stay competitive in the market.

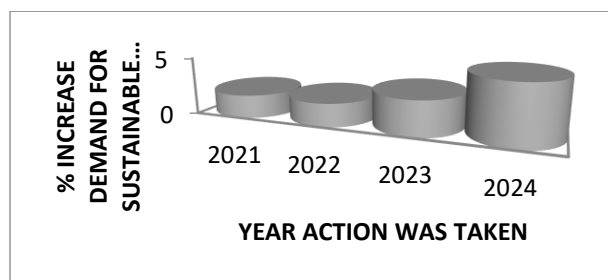


FIGURE 1: A CHART SHOWING THE GLOBAL DEMAND FOR SUSTAINABLE MATERIALS OVER RECENT YEARS

2. Objectives

The objective of this review is to systematically summarize and critically evaluate the current state of knowledge on mangosteen pericarp-based composites, with a focus on their preparation, properties, and potential applications, in order to identify gaps, challenges, and future directions for research and development in this field.

3. Review

Laongdaw Techawinyutham, Wiroj Techawinyutham, et al. developed lignocellulose-based biofiller-reinforced biopolymer composites from fruit peel wastes as natural pigments. Mangosteen peel and durian peel powders were combined and used as bio fillers in polybutyrate adipate terephthalate (PBAT). The resulting black composite material has potential applications in food packaging and medicine zipper packaging. The study examined the color change, morphological, chemical composition, mechanical, thermal, and rheological properties of the composites. The results showed that mangosteen/PBAT composites had superior thermal stability, mechanical properties, and dark color compared to durian/PBAT composites. However, durian/PBAT composites exhibited better thermal and rheological properties. [4]

Fairuz Septiningrum, Akhmad Herman Yuwono, et al. studied the synthesis of Ag/TiO₂ Nano composites using mangosteen pericarp extract as a reducing agent via a green chemistry approach. The Ag/TiO₂ Nano composites demonstrated adsorbent photo catalytic activity. The Nano composites were characterized using various techniques, including X-ray powder diffraction (XRD), Fourier transform infrared spectroscopy (FT-IR), UV-Vis spectrophotometry, scanning electron

microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), transmission electron microscopy (TEM), zeta potential measurement, and nitrogen (N₂) adsorption-desorption analysis.[5]

Asep Bayu Dani Nandiyanto, et al. conducted research on the effect of mangosteen peel compositions as reinforcement components on resin-based brake pad performance using computational bibliometric mapping analysis. Mangosteen peel compositions have been investigated for their potential as reinforcement components in resin-based brake pad performance, utilizing computational bibliometric mapping analysis. The incorporation of mangosteen pericarp particles with a suitable resin and a hardener resulted in a reinforcing component in brake pads. The results of physical and mechanical tests showed that the addition of more mangosteen rind particles resulted in harder brake pads [6]. Arkarapol Thumwon, et al. explored the use of fruit peel powder (FPP) from mangosteen, pomelo, and durian as natural antioxidants and reinforcing bio-fillers in natural rubber latex gloves. The use of fruit peel powder (FPP) from mangosteen, pomelo, and durian as natural antioxidants and reinforcing bio-fillers in natural rubber latex gloves has been investigated. Natural rubber latex gloves were improved using the peel powders. A comprehensive investigation was conducted on the morphology, functional group, particle size, and thermal stability of the fruit peel powders and natural rubber latex, both before and after the addition of the peel powders. The addition of fruit peel powder was found to increase the strength and capability of the gloves against oxidative degradation [7]. A study by A Muhammad, A Roslan, et al. investigated the mechanical properties of bio plastics formed from cellulose Nano crystal (CNC) mangosteen peel using glycerol as a plasticizer. This research focused on cassava starch as the matrix and cellulose Nano crystal from mangosteen peel as the reinforcing filler. The synthesis of bio plastics involved combining cassava starch as the matrix with cellulose Nano crystal from mangosteen peel as the reinforcing filler. Cellulose Nano crystal was added in varying proportions to the matrix, including 1g, 2.5g, and 5g. The results showed that the addition of mangosteen peel-based CNC improved the mechanical properties of the bioplastic. These improvements were confirmed through testing using a UTM universal testing machine, which demonstrated enhanced mechanical properties. Furthermore, FTIR analysis revealed distinct absorption patterns in the cellulose Nano crystal. Ultimately, the study proved that the mechanical properties of bio plastics were enhanced by adding CNC at various concentrations [8]. Arya Dwi Cahyo Utomo et al. prepared ZnO/TiO₂ Nano composites using the sol-gel method for enhanced light harvesting efficiency in solar cells. The preparation process involved adding titanium



dioxide to the ZnO matrix in varying ratios and measuring its impact on solar cells based on the DSSC system [9]. A dye extracted from mangosteen rind was utilized in the electrode by dissolving it in various solvents, including water, ethanol, and acetic acid. The maximum wavelength of the dye was measured using UV-visible spectroscopy. Characterization techniques, such as powder X-ray diffraction, ultra-violet spectroscopy, and scanning electron microscope-energy dispersive X-ray (SEM-EDX), demonstrated the diversity of surface morphology [9]. The results indicated that the addition of TiO₂ to the ZnO matrix influenced the structure of the Nano composite, making it suitable for application as DSSC electrodes [9].

Xi Huang, Xin Zhou, et al. investigated the antibacterial, antioxidation, and UV-blocking properties of biodegradable soy protein isolate food packaging film incorporated with mangosteen peel extract and ZnO nanoparticles [10]. A functional biodegradable soy protein isolate (SPI) food packaging film was developed by adding mangosteen peel extract, zinc oxide nanoparticles, and modifiers of different concentrations to a natural polymer using the casting method. The physical, antioxidant, antibacterial properties, and chemical structures of the film were examined. The composite film exhibited excellent UV-blocking, antioxidant, and antibacterial properties against microorganisms like *Escherichia coli* and *Staphylococcus aureus*. Thermogravimetric analysis (TGA) results showed that the thermal stability of SPI films was improved. Scanning electron microscopy (SEM) revealed the smooth surface and microstructure of the composite films. The strong hydrogen bonding in isolated soy protein and zinc oxide nanoparticles in the film were confirmed using attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) and X-ray photoelectron spectroscopy (XPS) analyses. Energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) were used to prove the presence of nanoparticles in the composite film [10]. The study suggests that the SPI/MPE/ZnO composite film is suitable for active food packaging to prolong the shelf life of food materials [10]. Siriporn Taokaew, Nadda Chiaoprakobkij, et al. studied the development of multifunctional cellulosic nanofiber film with enhanced antimicrobial and anticancer properties by incorporating ethanolic extract of *Garcinia mangostana* peel. Bacterial nanocellulose (BC) films were incorporated with mangosteen peel extract at different concentrations and assessed as a multifunctional nanofiber film. The mangosteen peel extract was absorbed and air-dried to entrap the extract. The resulting films showed enhanced antimicrobial activities. High anticancer activity against B16F10 melanoma and MCF-7 breast cancer cells was

detected after treatment with the film, with cell viabilities of 10% and 5%, respectively, after 48 hours. The research proposed that the prepared films were multifunctional nanofiber films possessing antimicrobial and anticancer properties [11]. Research by Nattapol Boonmak, Jitti Niyompanich, et al. focused on preparing mangosteen extract-loaded poly (vinyl acetate) for use as an antibacterial spray-on dressing. The study involved combining poly (vinyl acetate) film with mangosteen extract in different ratios, resulting in films with good antibacterial activity. The preparation of the film involved using ethyl acetate, ethanol, and propanol in ratios of 30, 50, and 20, respectively, with 1%, 2%, and 3% mangosteen extract. Cytotoxicity assessments confirmed that the polyvinyl acetate/mangosteen film was non-toxic and did not interfere with cells. Furthermore, *in vitro* biocompatibility was evaluated using L929 mouse fibroblasts, normal human fibroblasts, and keratinocyte cells. The results showed that the mixture with a higher concentration of mangosteen extract exhibited greater drug release. The study concludes that the MG/PVAc film spray can function as an effective antibacterial spray-on dressing [12].

Mohammad Aminuzzaman et al. synthesized zinc oxide nanoparticles using a green method, employing the aqueous extract of *Garcinia mangostana* fruit pericarp as a reducing and capping agent. Various characterization techniques, including X-ray diffraction, Fourier transform infrared spectroscopy, field emission scanning electron microscopy, transmission electron microscopy, energy dispersive X-ray spectroscopy, and UV-visible spectroscopy, were used to distinguish the biosynthesized ZnO nanoparticles. The resulting ZnO nanoparticles were spherical in shape, with a size of 21 nm, and exhibited high purity, leading to excellent photo catalytic performance. The photo catalytic activity of the biosynthesized ZnO nanoparticles was evaluated by degrading malachite green dye under solar irradiation.[13]

Mingzhe Xue et al. developed a method to synthesize mangosteen peel-derived porous carbon and explored its application in the sulphur cathode for lithium-sulphur batteries. The activation process was used to synthesize porous carbon with a pore size of less than 2 nm to 0-4 nm at a low activation temperature of 700°C. A high surface area (>3000 m² g⁻¹) porous carbon was obtained at an activation temperature of 800°C. The porous carbon was then used to form a carbon-sulphur composite, which was applied as a cathode for lithium-sulphur batteries. The hierarchical porous carbon/sulphur composites demonstrated great specific discharge capacities of more than 800 mAh g⁻¹. [14] YJ Machado and W Murillo-Aranguren et al. evaluated the potential of mangosteen peel extract as a natural dye, antioxidant, and additive in fruit beverages. The study assessed the



antioxidant capacity, phenolic content, dye stability, and yield of extracts from different divisions of the mangosteen peel. The extract was obtained using water, ethanol, and different mixtures. Physicochemical and microbiological stability were measured to determine whether the beverage met current regulations. The color stability of the beverage was also evaluated over 30 days using a hedonic scale. The mixture of water and ethanol in a 1:1 ratio showed the best extraction performance, yielding $23.07 \pm 0.12\%$ of total biomass extracted from the peel.[15] Kar Xin Lee et al. studied the bio-mediated synthesis and characterization of silver nano-carriers and their potent anticancer action. The biosynthesis of silver nanoparticles (AgNPs) was demonstrated using a waste material and mangosteen fruit peel extract. The study showed that Nano-particle-based drug carriers can deliver drugs to targeted tissues, and the efficiency of penetration into tumor cells was improved. Silver Nano-particles were synthesized using mangosteen peel, and protocatechuic acid, a plant-based drug, was used to test its efficiency. The results showed that silver Nano-particles loaded with protocatechuic acid exhibited about 80% inhibition, higher than Ag Nano-particles alone. Additionally, the silver Nano-particles were found to be non-toxic when tested on normal colon cells.[16]R.A. Ilyas, S.M. Sapuan, et al. conducted a comparative study on macro to Nano-scale natural fiber composites for automotive components, focusing on research, development, and application aspects. The study highlighted the current growth and improvements of natural fiber polymer composites in various fields. These biodegradable, renewable composite materials possess important mechanical and barrier properties, making them applicable in various fields. The study concluded that natural fiber polymer composites have potential automotive applications from macro to nano-scale.[17] S. Wahyuningsih, A. H. Ramelan, et al. investigated the use of anthocyanin's as a TiO_2 -sensitizer in Rhoda mine B photoelectrodegradation for water purification. Anthocyanin's, a natural dye extracted from mangosteen peel, were used as a sensitizer in TiO_2 /anthocyanin photo anodes. The study showed that anthocyanins are a promising alternative to hazardous heavy metal systems. The photodegradation of rhodamine B impurity in water was evaluated under halogen lamps, and the results showed that the addition of NaCl electrolyte significantly influenced the photoelectrodegradation process [18].

Asma Nasrullah, Amir Sada Khan, et al. developed mangosteen peel-alginate biocomposites beads as an efficient and sustainable adsorbent for decontamination of methylene blue. The biocomposites were characterized using FTIR, FESEM, BET, and TGA techniques to analyze surface functional groups, surface morphology, surface properties, and thermal stability.

The adsorption efficiency was tested, and the results showed greater removal capacity in alkaline medium. Kinetic and isotherm studies revealed that the adsorption process followed pseudo-second-order kinetic models and both Freundlich and Langmuir isotherms. The study concluded that mangosteen peel-alginate biocomposites can be used as a good adsorbent in textile industries.[19].Nadda Chiaoprakobkij, Sutasinee Seetabhawang, et al. developed multifunctional bacterial cellulose-gelatin containing mangosteen extract films with improved antibacterial and anticancer properties. The films were prepared using a simple casting method, and biocomposites were prepared using mechanically modified bacterial cellulose, gelatin, and mangosteen peel at different concentrations. The results showed that the films exhibited excellent antibacterial activity against *E. coli* and *S. aureus*, and anticancer activities against human oral cancer cells. The study concluded that cellulose-gelatin containing mangosteen extract films showed excellent antibacterial and anticancer activities.[20] S Pinmongkhonkul, T Panyopo, et al. produced cellulose films from the pseudo-stem of Namwa Banana (*Musa X Paradisiaca L.*) mixed with crude extract of mangosteen peel (*Garcinia Mangostana*). The mangosteen rind extract was mixed with cellulose from the pseudo-stem of Namwa banana in different concentrations for comparative studies. The results showed improved properties with mangosteen rind extract, including preservation of fruits, biodegradation, and antimicrobial activity of cellulose. The study concluded that cellulose films with mangosteen peel extract are a better option for the future.[21]

Asranudin, Nouredine, et al. fabricated a sustainable adsorbent, nanocellulose-mesoporous hectorite bead, for methylene blue adsorption [23]. The adsorbent was synthesized using mangosteen rind, a rich source of cellulose content, mesoporous hectorite, and alginate through acid hydrolysis. The functional group, phase, and morphology of the composite were investigated. The results showed that mesoporous hectorite significantly contributed to the adsorption capacity. The equilibrium adsorption data followed the Freundlich isotherm, and thermodynamic studies revealed a spontaneous and endothermic process. The study concluded that nanocellulose-hectorite-alginate bead composites can be used as an adsorbent for water purification.[22]. H Guo, Z Yue, C Shao, et al. developed intelligent carboxymethyl cellulose composite films containing *Garcinia mangostana* shell anthocyanin with improved antioxidant and antibacterial properties. The composite films were synthesized using solution blending and solution casting methods. Mangosteen shell extract was used as a pH indicator. The study examined the structure, physical properties, antioxidant, and antibacterial



properties of the composite films. Fish freshness tests were conducted to evaluate the efficiency of the composite films. The results showed excellent mechanical properties, low water vapour permeability, and outstanding UV-blocking performance. The study introduced new concepts and possibilities for intelligent packaging composite films [23]

Mohd Salahuddin Mohd Basri et al. discussed the progress in valorizing fruit and vegetable wastes, focusing on active packaging, biocomposites, by-products, and innovative technologies for bioactive compound extraction. The study highlighted the potential

of organic wastes, such as seeds, skins, and bark, which are rich in nutrients, phytochemicals, fibers, and oils. The researchers emphasized the need to address environmental pollution caused by fruit and vegetable wastes from the food bioprocessing industry. The study explored new research and innovation connected to food, packaging, and pharmaceutical uses, including the use of seed, skin, and rind of plants as sources of vitamins, phytochemicals, enzymes, bioactive compounds, and nutrients.[24]

Table 1: A table listing utilization of mangosteen pericarp in composites, observation and their results.

No	UTILIZATION OF MANGOSTEEN PERICARP	COMPOSITES	OBSERVATIONS	RESULTS
1.	Mangosteen pericarp extract as pH indicator.	Carboxy methyl cellulose films[casting method]	Physical properties, Antioxidant and antibacterial properties were discussed.	It shows improved antibacterial and antioxidant properties
2.	Cellulose content of Mangosteen pericarp extract	Nanocellulose-hectorite - Alginate bead composites. [Acid hydrolysis process]	Functional group, Phase and morphology of composite investigated.	NCHABC can be used as an adsorbent for water purification.
3.	Extract of Mangosteen peel and	Cellulose films	Tensile strength, water vapour transmission rate, Biodegrad	With mangosteen peel extract cellulose films shows
4.	Mangosteen pericarp extract	SPI/MP E/ZnO Composite		Antibacterial, Antioxidant properties, chemical structure
5.	Mangosteen pericarp extract as reducing agent.	AgO/TiO ₂ Nano composite[Green chemistry]		Zeta potential measurement and Nitrogen adsorption-desorption analysis.
6.	Mangosteen peel powder and Durian peel powder as Biofiller.	Mangosteen/PBAT Composite, Durian/PBAT Composite		Colour change, Morphological, Chemical composition, Mechanical, Thermal and Rheological properties were studied.
	Namwa banana			ation, Antimicrobial activity
				better property.
				Capable for active food packaging, Improve shelf life of food materials.
				It shows adsorption-photo catalytic activity.
				Mangosteen/PBAT Composite were superior to Durian/PBAT Composite in Thermal stability and Mechanical



				properties.
7.	Dye extract of Mangosteen pericarp	ZnO/TiO ₂ Nano composite	Wavelength of dye measured using UV-Visible Spectroscopy	Composite can be applied in DSSC electrodes

4. Discussion

Existing Materials: Limitations and Drawbacks

Traditional materials like carbon fibre, glass fibre, and synthetic polymers have been widely used in various industries. However, they have several limitations and drawbacks. Carbon fiber, for instance, is expensive, non-biodegradable, and has limited recyclability. Glass fiber, on the other hand, has limitations in terms of mechanical properties and can be brittle. Synthetic polymers like polyethylene and polypropylene are non-biodegradable, non-renewable, and contribute to environmental pollution [3].

Biodegradable Materials: Inadequate Mechanical Properties

Biodegradable materials like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based bio plastics have been developed as alternatives to synthetic polymers. However, these materials often have inadequate mechanical properties, limited scalability, and high production costs [25]. For instance, PLA has limited thermal stability and can be brittle. PHA has high production costs and limited availability [26].

Nano-Hybrid Composites: Enhanced Properties

Nano-hybrid composites, on the other hand, have shown enhanced properties compared to traditional materials. These composites combine the benefits of nanomaterials and hybrid materials, resulting in improved mechanical, thermal, and electrical properties. However, most Nano-hybrid composites are based on non-renewable and non-biodegradable materials, which can contribute to environmental pollution. The convergence of nanomaterials and nanotechnology has ushered in a transformative era across diverse scientific and technological domains. By harnessing the unique attributes of nanomaterials, researchers have made significant strides in developing innovative

electrochemical sensors and biosensors. These advancements have far-reaching implications for detecting toxic substances, monitoring environmental pollutants, and improving human life quality and environmental protection. Notably, nanomaterials have been employed in various applications, including environmental monitoring, detection of toxic contaminants in drinking water, and development of fluorescent biosensors for tracking environmental pollutants. Furthermore, Nano sensors and biosensors have been explored for detecting air pollution, while nanostructure-modified electrodes have been utilized for electrochemical detection of emerging contaminants. A key factor contributing to the success of nanomaterial's in sensor applications is their distinctive properties, such as high surface-to-volume ratio, adjustable optical and electrical characteristics, and enhanced sensitivity and selectivity. Recent progress in electrochemical sensor platforms has focused on leveraging a diverse range of nanomaterials, including MXene, carbon nanomaterials, metal oxide nanomaterials, metal nanoparticles, biomaterials, polymers, and hybrid materials. The integration of these nanomaterials has significantly enhanced the sensitivity and performance of electrochemical sensors, driving substantial advancements in environmental monitoring, healthcare, and other fields. As research in this area continues to evolve, it is anticipated that nanomaterial's will play an increasingly vital role in addressing pressing global challenges.[27]

Mangosteen Pericarp-Based Nano-Hybrid Composites: Sustainable and Superior

Mangosteen pericarp-based nano-hybrid composites offer a sustainable and superior alternative to existing materials. These composites are biodegradable, non-toxic, and renewable, making them an environmental friendly option. Additionally, mangosteen pericarp-based nano-hybrid composites have shown enhanced mechanical, thermal, and electrical properties compared to traditional materials. The unique combination of mangosteen pericarp and nano-hybrid materials results in a composite material that is not only sustainable but also superior in terms of performance. These composites, derived from the pericarp of mangosteen fruit, offer a unique combination of biodegradability, non-toxicity, and renewability. Unlike traditional composites, which often rely on non-renewable resources and generate hazardous waste, mangosteen pericarp-based Nano-hybrid composites provide a sustainable alternative. Their superior properties, including enhanced mechanical strength, thermal stability, and electrical conductivity, make them an attractive material for various applications, such as mangosteen pericarp-based



Nano-hybrid composites have been explored as electrode materials for super capacitors and batteries, demonstrating improved performance and sustainability. These composites have been investigated for biomedical applications, and non-toxicity Mangosteen pericarp-based Nano-hybrid composites have been used for the removal of heavy metals and organic pollutants from wastewater, showcasing their potential for environmental remediation. These composites have been explored as sustainable packaging materials, offering improved barrier properties and biodegradability. The production process of mangosteen pericarp-based Nano-hybrid composites is also environmentally friendly. The extraction of mangosteen pericarp is a simple and cost-effective process. In addition to their sustainable production process and superior properties, mangosteen pericarp-based Nano-hybrid composites also offer a unique opportunity for waste reduction and valorization. The use of mangosteen pericarp, a waste material that would otherwise be discarded, reduces the environmental impact of waste disposal and promotes a more circular economy. Overall, mangosteen pericarp-based Nano-hybrid composites embody a perfect synergy of sustainability and superiority, rendering them an ideal material for future applications.

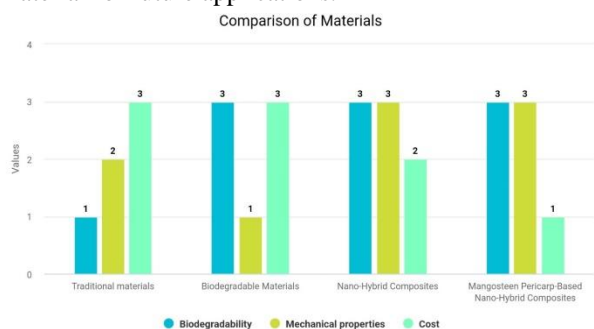


FIGURE 2: COMPARISON OF MATERIALS

Biomass-Based Hybrid Nanocomposites: A Comparative Analysis

Mangosteen biomass-based hybrid Nano composites have emerged as a promising class of materials due to their unique combination of properties. Derived from the pericarp of the mangosteen fruit, these composites exhibit high thermal stability, mechanical strength, and antioxidant activity, making them suitable for various applications such as energy storage, biomedical devices, and sustainable packaging [25][26]. Mangosteen pericarp, the outer rind of the mangosteen fruit (*Garcinia mangostana*), has garnered attention in recent years for its potential applications in the development of hybrid

nanocomposites. Traditionally, various forms of biomass have been utilized to reinforce nanocomposites, aiming to enhance their mechanical, thermal, and functional properties. This comparative study explores the advantages of mangosteen pericarp-based hybrid Nano composites over conventional biomass-based counterparts, focusing on mechanical reinforcement, antioxidant properties, and environmental sustainability. Incorporating natural fillers into polymer matrices is a common strategy to improve the mechanical properties of bio plastics. A study by Sansui et al. investigated the use of cellulose nanocrystals (CNCs) derived from mangosteen peel in bio plastic production. The findings indicated that the addition of CNCs enhanced the tensile strength and flexibility of the bio plastic, overcoming the inherent brittleness and low strength associated with traditional starch-based bio plastics. The CNCs acted as effective reinforcing agents, leading to improved mechanical performance of the composite material.[28] In contrast, other biomass-derived fillers, such as durian peel fibers, have been used to reinforce thermoplastic cassava starch composites. While the addition of these fibers improved tensile and flexural properties, the optimal performance was observed at a specific fiber content (40 wt%). Beyond this point, the mechanical properties did not show significant enhancement, indicating a limitation in the reinforcing capability of durian peel fibers compared to mangosteen-derived CNCs. [29] A distinctive advantage of mangosteen pericarp-based Nano composites is their inherent antioxidant properties. The pericarp is rich in xanthones, particularly α -mangostin, which exhibit strong antioxidant activity. When incorporated into nanofiber mats, mangosteen pericarp extract not only contributes to the structural integrity of the composite but also imparts significant antioxidant properties. This dual functionality is beneficial in applications where both mechanical strength and oxidative stability are desired. [30] Other biomass-based fillers, such as pineapple leaf fibers or durian peel fibers, primarily serve as mechanical reinforcements and lack the bioactive compounds necessary to provide antioxidant benefits. Therefore, mangosteen pericarp-based Nano composites offer a unique advantage by combining mechanical reinforcement with bioactive functionalities. The utilization of mangosteen pericarp in Nano composite production aligns with principles of environmental



sustainability. Mangosteen pericarp is often considered agricultural waste, and its use as a filler material promotes waste valorization and resource efficiency. The extraction of cellulose nanocrystals from the pericarp involves processes such as delignification, bleaching, and hydrolysis, which are relatively straightforward and can be conducted under mild conditions. [4] Similarly, other biomass sources like durian peel fibers have been explored for reinforcing bio plastics, contributing to waste reduction and the development of sustainable materials. However, the additional bioactive properties of mangosteen pericarp, such as its antioxidant activity, provide an extra layer of functionality that is not present in other biomass-derived fillers. Mangosteen pericarp-based hybrid Nano composites demonstrate superior performance compared to traditional biomass-based Nano composites in several key areas. The incorporation of cellulose nanocrystals from mangosteen pericarp enhances the mechanical properties of bio plastics, providing greater tensile strength and flexibility. Additionally, the inherent antioxidant properties of the pericarp impart added functionality to the composites, making them suitable for applications requiring both structural integrity and oxidative stability. Furthermore, the use of mangosteen pericarp promotes environmental sustainability through the valorization of agricultural waste. These combined advantages position mangosteen pericarp-based Nano composites as a promising alternative to existing biomass-based materials in various industrial applications. A distinctive advantage of mangosteen pericarp-based Nano composites is their inherent bioactive properties. The pericarp is rich in xanthones, particularly α -mangostin, which exhibit strong antioxidant activity. Sriyanti et al. (2018) embedded mangosteen pericarp extract into electrospun polyvinylpyrrolidone (PVP) nanofiber mats, resulting in a composite with significant antioxidant properties. This dual functionality is beneficial in applications where both mechanical strength and oxidative stability are desired. Other biomass-based fillers, such as durian peel fibers, primarily serve as mechanical reinforcements and lack the bioactive compounds necessary to provide antioxidant benefits.

Mangosteen-based brake pads exhibit superior properties compared to the other studies. With a wear rate of 0.64, mangosteen-based brake pads outperform the carbon nanotube-based brake pads (2.15 mg/m), *Allium sativum*

fiber-based brake pads (higher wear loss), sorghum husk-derived Si₃N₄ and biochar-based brake pads (0.12 mm³/Nm), and other biomass-based brake pads such as banana (1.2-1.5), coconut (1.5-2.0), pineapple (1.8-2.2), sugarcane (1.2-1.5), and rice (1.5-2.0). Additionally, mangosteen-based brake pads demonstrate a higher hardness level, with a maximum friction coefficient of 0.69, surpassing the other studies. The optimal composition of mangosteen peel particles and resin (MA) yields the best ratio of resin to mangosteen peel mixture, resulting in improved mechanical properties. Furthermore, mangosteen-based brake pads show a higher thermal stability and resistance to fade, with a friction coefficient comparable to the *Allium sativum* fiber-based brake pads (0.69×10⁻⁵ vs. 12.37% fade rate and 110.40% recovery rate). The *Allium sativum* fiber-based brake pads also exhibit a lower wear loss, but the mangosteen-based brake pads have a more consistent friction coefficient. In contrast, the sorghum husk-derived Si₃N₄ and biochar-based brake pads exhibit a lower thermal conductivity (0.214 W/mK) and improved mechanical properties, including tensile strength (138 MPa), flexural strength (192 MPa), impact strength (6.7 J/m), compression strength (152 MPa), and hardness (94 Shore D). The carbon nanotube-based brake pads, on the other hand, require an optimal processing parameter of 1.5 wt% carbon nanotube, 0.5AgNPs, 100 °C curing temperature, 20 MPa moulding pressure, and 5-h curing time to achieve a wear rate of 2.15 mg/m and hardness of 125 HRB. Overall, mangosteen-based brake pads offer a superior combination of wear resistance, hardness, friction coefficient, thermal stability, and eco-friendliness, making them an attractive alternative for brake pad applications.[31][32][33].

Researchers have been exploring the potential of natural antioxidants and biodegradable materials for food packaging. Studies investigated the use of mangosteen pericarp extract (MPE) as a natural antioxidant in biodegradable films. The effect of MPE on the physicochemical properties of fish gelatin (FG), soy protein isolates (SPI), and corn starch (CS) films. The results showed that MPE increased the water vapour permeability and reduced the mechanical properties of the films. However, SPI films with 5% MPE exhibited the highest antioxidant capacity, with a DPPH- In contrast, an overview of the development of biomass food packaging films, including scavenging activity of



92.67%.cellulose, starch, chitosan, and gelatine. The study analysed the properties, preparation methods, and applications of these films in food packaging. The results highlighted the potential of biomass films to provide functional properties such as antimicrobial, preservation, and indication. The study also emphasized the need for continued material innovation and technological improvements to meet specific packaging needs. A comparison of these studies reveals that the use of MPE as a natural antioxidant in biodegradable films shows promise for improving the functional properties of these materials. The first study demonstrated the potential of MPE to enhance the antioxidant capacity of SPI films, while the second study highlighted the broader potential of biomass films for food packaging applications. Overall, these studies contribute to the development of sustainable and eco-friendly food packaging solutions.[34][35].

A comparative study of mangosteen pericarp-based composites, cellulose-based composites, lignin-based hydrogels, and natural fiber-reinforced polymer composites reveals their potential for biomedical applications. Biodegradable composites derived from plant-based biomass have garnered significant attention due to their sustainability, biocompatibility, and biodegradability. Mangosteen pericarp-based composites exhibit high antimicrobial and antioxidant activities, making them suitable for wound healing, tissue engineering, and drug delivery. The optimized extraction of α -mangostin from mangosteen pericarp using microwave-assisted extraction has further enhanced their biomedical applications. With its high α -mangostin concentration and secondary metabolite content, mangosteen pericarp-based composites exhibit higher antioxidant and antibacterial activities, particularly against Gram-positive bacteria[36].Cellulose-based composites, widely used in biomedical applications, demonstrate excellent biocompatibility, biodegradability, and mechanical properties.[37] However, their antimicrobial and antioxidant activities are limited. Cellulose-based composites have been explored for wound dressing, tissue engineering, and drug delivery applications. Lignin-based hydrogels have been investigated for tissue engineering, wound healing, drug delivery, and 3D bio printing. Although they exhibit some antimicrobial and antioxidant activities, their mechanical properties and

biological activities are inferior to those of mangosteen pericarp-based composites.[38][39][40] Natural fibre-reinforced polymer composites, which rely on natural fibers for strength and synthetic or bio-resin matrices for binding, demonstrate improved mechanical properties. However, they lack antimicrobial and antioxidant activities, limiting their biomedical applications. [41] In comparison, mangosteen pericarp-based composites offer a unique combination of high antimicrobial and antioxidant activities, excellent biocompatibility, and biodegradability. Their potential for biomedical applications, including wound healing, tissue engineering, and drug delivery, makes them an attractive alternative to traditional biomass-based composites.

Mangosteen-based biocomposites exhibit superior adsorption properties compared to other biomass-based composites. With a maximum absorption capacity of 486.8 mg/g and an adsorption rate of 97.4% in 30 minutes for Congo red dye, mangosteen-based biocomposites outperform soybean dreg/hydrocalumite composites and Ag/TiO₂ Nano composites. The unique adsorption properties of mangosteen-based biocomposites can be attributed to the high α -mangostin concentration and secondary metabolite content, which enhance their antioxidant and antimicrobial activities. Lignocellulosic biomass, including crops, agricultural wastes, and forest residues, offers a sustainable and abundant resource for producing robust materials that can eliminate various pollutants from wastewater. Valorising biomass wastes is a strategic approach that reduces waste quantity while leveraging its physicochemical properties. Lignocellulosic biomass is rich in cellulose, hemicellulose, and lignin, which have proven efficient in removing persistent pollutants. These biomass materials can undergo physical, chemical, and thermal modifications to produce cellulose Nano crystals and biochar with enhanced removal abilities. In comparison, other biomass-based composites, such as algal waste-based composite materials and biomass carbon-based montmorillonitecomposites, have also shown promise in removing pollutants from wastewater. The physical characteristics of these bio sorbents, including surface area, porosity, size distribution, and density, significantly influence the adsorption process. Overall, mangosteen-based biocomposites, lignocellulosic biomass-based materials, and other



sustainable biomass-based composites offer unique advantages in wastewater remediation, providing efficient and environmentally friendly solutions for pollutant removal.

[42-45]

5. Applications and Future Scope

The unique characteristics of MPNHBC make them capable for a diverse range of applications. These can degrade organic pollutants like methylene blue dye through adsorption and photo degradation [46]. These are used in different areas such as automotive, construction, space, marine and in electrical machineries. In addition MPNHBC possess greater thermal and rheological properties which makes them suitable for food packaging and medicine zipper packaging [3]. More number of MP particles improves their physical and mechanical properties, [5] which applicable them in the formation of Bio plastics which is a good and eco-friendly alternative to conventional plastics and in the production of brake pads. Adsorption property makes them use in DSSC electrodes [8], photocatalytic activity and lithium sulphur batteries. MPNHBC possess antibacterial activities can make them applicable to drug release, composite films, antibacterial spray on dressing. Their biodegradability, renewability and barrier properties make it significant in opto electronics, optical devices, paper making, and pharmacological products. Additionally their biocompatibility makes them ideal for biomedical application such as drug delivery systems and engineering. The future scope of MPNHBC is promising with on-going research focused on enhancing their properties and expanding their applications. The development of new synthesis techniques and

exploration of other natural sources for nanoparticles could further advance the field of biocomposites. These have the potential to replace non degradable polymers that create environmental impacts. Larger sustainability considers for biocomposites will still essential to be accompanied to moderate ecological and commercial hazards to make sure vigorous elucidations [47]. Through the improvement of technology to make great performance biodegradable plastics; biopolymers are employed in agriculture, packing, medicals etc. MPNHBC discloses new-fangled promising applications with boundless potential for the industrial revolution in near future [48]. Figure 3 shows the infographic representation of applications of mpnhbc in various industries. A consolidation of various characterization techniques used for the synthesis of MPNHBC, and its applications is shown below in table 2.

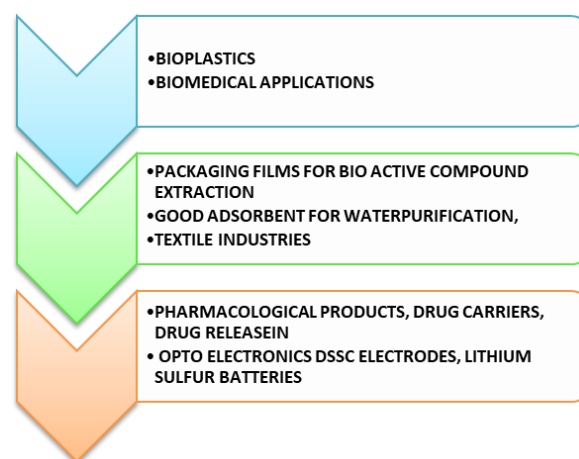


FIGURE 3: INFOGRAPHIC REPRESENTATION OF APPLICATIONS OF MPNHBC IN VARIOUS INDUSTRIES

Table 2: A table listing various characterization techniques used for the synthesis of MPNHBC, and its applications

NO	NAME OF BIOCOMPOSITES	CHARACTERIZATION	APPLICATIONS
1	Ag/TiO ₂ Nano composite	X-ray powder diffraction (XRD), Fourier transformation infrared spectroscopy (FT-IR), UV-Vis spectrophotometer, Scanning electron microscopy (SEM), Energy dispersive X-ray spectroscopy (EDS), Transmission electron microscopy (TEM), Zeta potential measurement, and nitrogen (N ₂) adsorption-desorption analysis	Organic pollutant degradation by adsorption-photo catalytic activity
2	Cellulose Nano crystal	FTIR	Bio plastics



3	ZnO/TiO ₂ Nano composite	X-ray diffractions characterise Nano composites, ultra violet spectroscopy, scanning electron microscope-energy and dispersive X-ray (SEM-EDX) demonstrated the diversity of surface morphology	DSSC electrodes
4	SPI/MPE/ZnO composite film	ATR-FTIR and XPS analyses. EDX and XRD, TG (Thermo gravimetric analysis), SEM (SCANNING ELECTRON TRANSMISSION SPECTROSCOPY)	Food packaging

5.0 CONCLUSION

In conclusion, Mangosteen Pericarp Based Nano Hybrid Biocomposites represent a significant advancement in polymer science. Their biodegradability, renewability, and superior properties make them a convincing substitute to synthetic composites. This analysis highlights various processing methods and its potential application including challenges, opening in the improvement of sustainable biocomposites from agricultural waste biomass. Emergent need and demands for better performance materials entice the usage of Nano hybrid biocomposites. Researchers have concentrated on them for the further inventiveness in properties of products and in that way increasing the application level. As research continues to progress, MPNHBC are poised to play a vital role in the development of sustainable materials for a multitude of applications. Biomass based composites from MP offers a promising route towards a more ecologically friendly future.

References

- Friedrich Munder, Christian Fürll, Heinz Hempel *Natural Fibers, Biopolymers, and Biocomposites* 1st Edition Imprint CRC Press Pages 33 eBook ISBN 9780429211607, 2005
- R. Bhat, G. Paliyath, in *Encyclopedia of Food and Health*, 2016
- Laongdaw Techawinyutham, Wiroj Techawinyutham, et.al Lignocellulose based biofiller reinforced biopolymer composites from fruit peel wastes as natural pigment *Journal of biological macromolecules* volume.257, part 2, (2024).
<https://doi.org/10.1016/j.ijbiomac.2023.128767>
- Fairuz Septiningrum, Akhmad Herman Yuwono et.al *current research in green and sustainable chemistry* volume 8, 100394. 2024
- Asep Bayu Dani Nandiyanto, Dwi Fitria et.al *Materials Physics and Mechanics*. pages 37-55, 2020
- A Thumwong, J Darachai, N Thamrongsiripaket.al - *Antioxidants*, 2023 Volume 12 Issue 5 ,10.3390/antiox12051119 - [mdpi.com](https://www.mdpi.com) 2023
- A Muhammad et al *Journal of Phy. Conf. Ser.*, 1349 012099, 2019
- Arya Dwi Cahyo Utomo et.al Indo. J. Chem. Res., 10, 68-73., 2022
- X Huang, X Zhou, Q Dai, Z Qin - *Nanomaterials*, - [mdpi.com](https://www.mdpi.com), 2021
- S Taokaew, N Chiaoprakobkij, and P Siripong- *Materials Science and Engineering* Volume 120 C 120:111783, January 2021.
<https://www.sciencedirect.com/journal/materials-science-and-engineering-c/vol/120/suppl/C>
- N Boonmak, J Niyompanich, P Chuysinua - *Journal of Drug Delivery* , – Elsevier, 2018
- Aminuzzaman, M., Ying, L.P., Goh, WS. et al. *Bull Mater Sci* 41, 50, 2018
<https://doi.org/10.1007/s12034-018-1568-4>
- M Xue, C Chen, Y Tan, Z Ren, B Li, C Zhang - *Journal of Materials Science*, – Springer Volume 53, pages 11062–11077, 2018
- YJ Machado, W Murillo-Arang *Iraqi Journal of Agricultural Sciences* –2022:53(4):857- 866 ..., 2022 -
- KX Lee, K Shamel, SE Mohamad, YP Yew - *Nanomaterials*, - [mdpi.com](https://www.mdpi.com), 2019
- RA Ilyas, SM Sapuan, NM Nurazz - *Biocomposites and synthetic composites for automotive application* , Pages 51-105, 2021
- S Wahyuningsih, AH Ramelan, et.al *Biophotonics Japan* volume 9792; 97921E Event: SPIE/OSJ., 2015 <https://doi.org/10.1117/12.2204943>



18. Amir Sada Khan, A. H. Bhat et.al [https://doi.org/10.21203/rs.3.rs-1038092/v1] 2021
19. Chiaoprakobkij, N., Seetabhawang, S., Okhawilai, M. 29, **6811–683**. <https://doi.org/10.1007/s10570-022-04685-5> 2022
20. Pinmongkhonkul, Sitthisak SSRN:. <http://dx.doi.org/10.2139/ssrn.4806280> or <https://ssrn.com/abstract=4806280>
21. Asranudin a, Noureddine et.al <https://doi.org/10.1016/j.cscee.2024.100850>
22. H Guo, Z Yue, C Shao, et.al *International Journal of Biological Macromolecules* **Volume 263**, Part 2, April 2024.
23. Mohd Salahuddin Mohd Basri et.al *Polymers* , 13(20), 350, 2021 <https://doi.org/10.3390/polym13101581>
24. Linh Nguyen Tran Cam et.al Journal home page for Heliyon A rising trend in eco-friendly products: A health-conscious approach to green Volume 9, Issue 9, September 2023, e19845 [https://www.cell.com/heliyon/fulltext/S2405-8440\(23\)07053-6](https://www.cell.com/heliyon/fulltext/S2405-8440(23)07053-6)
25. Aizat WM, Jamil IN, Ahmad-Hashim FH, Noor NM. 2019. Recent updates on metabolite composition and medicinal benefits of mangosteen plant. *PeerJ* 7:e6324 <https://doi.org/10.7717/peerj.6324>
26. Hourieh Tousian Shandiz, Bibi Marjan Razavi et.al Review of *Garcinia mangostana* and its Xanthones in Metabolic Syndrome and Related Complications 28 June 2017 <https://doi.org/10.1002/ptr.5862>
27. Ain Sansui et.al, Mechanical properties of bio plastic form cellulose Nano crystal mangosteen peel using glycerol as plasticizer *Journal of physics* 2019.
28. Zeba Tabassum a, Madhuri Girdhar et.al Mater Trash to treasure: advancing resource efficiency using waste-derived fillers as sustainable reinforcing agents in bio plastics *Adv.*, 2025, 6, 527-546 DOI: 10.1039/D4MA01043D
29. Sriyanti, Dhewa Edikresnha et.al *J Nano medicine* Mangosteen pericarp extract embedded in electrospun PVP nanofiber mats: physicochemical properties and release mechanism of α -mangostin 2018 Aug 31;13:4927–4941 doi:10.2147/IJN.S167670 DOI: 10.1039/D4MA01043D
30. Aigbodion, V.S. Unveiling optimisation of the manufacturing parameters of brake pad formulation developed from silver nanoparticle modified carbon nanotubes from rice husks. *stabilization.oref.* **15**, 3875–3890 (2025). <https://doi.org/10.1007/s13399-024-05384-w>
31. Kumar, V.V., Dhanalakshmi, S., Raghunathan, V. et al. Characterization of *Allium sativum* stalk-based biomass for automotive brake pad applications. *Biomass Conv. Bioref.* (2024). <https://doi.org/10.1007/s13399-024-05590-6>
32. Manoj, E., Selvakumar, G., Ram Prakash, S. et al. Characterization study on eco-friendly break pad material using sorghum husk-derived Si₃N₄ and biochar friction modifier. *Biomass Conv. Bioref.* **14**, 5735–5744 (2024) <https://doi.org/10.1007/s13399-023-04917-z>
33. Recent advances in research on biomass-based food packaging film materials Yanlu Mu, Shenghua Lv, Jinru Liu, Jiahao Tong, Leipeng Liu, Jiaqi Wang, Tingxiang He, Dequan Wei First published: 15 January 2025 <https://doi.org/10.1111/1541-43>
34. Nabilah, B., Wan Zunairah, W.I., Nor Afizah, M. et al. Effect of Mangosteen (*Garcinia mangostana* L.) Pericarp Extract on the Different Carriers for Antioxidant Active Packaging Films. *J Package Technol Res* **3**, 117–126 (2019). <https://doi.org/10.1007/s41783-019-00058-9>
35. Ghasemzadeh, A. et al, A. Alpha-Mangostin-Rich Extracts from Mangosteen Pericarp: Optimization of Green Extraction Protocol and Evaluation of Biological Activity. *Molecules* **2018**, *23*, 1852. <https://doi.org/10.3390/molecules23081852>
36. Yan Xue, Zihao Mou et.al Nanocellulose as a sustainable biomass material: structure, properties, present status and future prospects in biomedical application_Nano scale, 2017,**9**, 14758-14781 DOI <https://doi.org/10.1039/C7NR04994C>
37. Ravi Shankar, K, Venkatesan, M.; Desingh, R.P.; Mahalingam, A.; Sadhasivam, B.; Subramaniam, R.; Dhamodharan, R. Biocompatible hydrogels of chitosan-alkali lignin for potential wound healing applications. *Mater. Sci. Eng. C* **2019**, *102*, 447–457. [Google Scholar] [CrossRef] [PubMed]



38. Oveissi, F.; Naficy, S et.al; Fletcher et.al Tough and Processable Hydrogels Based on Lignin and Hydrophilic Polyurethane. *ACS Appl. Bio Mater.* **2018**, 1, 2073–2081. [[Google Scholar](#)] [[CrossRef](#)] [[PubMed](#)]
39. Spiridon, I.; Poni, P et.al Biological and pharmaceutical applications of lignin and its derivatives: A mini-review. *CellulChem. Technol.* **2018**, 52, 543–550. [[Google Scholar](#)]
40. Namvar, Farideh, et al. "Potential use of plant fibres and their composites for biomedical applications." *BioResources* 9.3 (2014)
41. Xiaodong Yang, Fangfei Li, Maosheng Xia, Feng Luo et.al Investigation on the micro-structure and adsorption capacity of cellulosic biomass carbon based montmorillonite composite, *Microporous and Mesoporous Materials* Volume 256, 15 January 2018, Pages 18-24
42. Chakhtouna, H., Benzeid, H., Zari, N. *et al.* Recent advances in eco-friendly composites derived from lignocellulosic biomass for wastewater treatment. *Biomass Conv. Bioref.* **14**, 12085–12111 (2024). <https://doi.org/10.1007/s13399-022-03159-9>
43. Bei TangGuanping PengDeyi LuoXi Zho et.al Preparation an Adsorption Properties of Soybean Dreg/Hydrocalumite Composites Vol 6/Issue 41ArticleOctober5,2020 *ACS Omega* <https://pubs.acs.org/doi/10.1021/acsomega.1c04460>
44. Aruna Yadav a, Nisha Bagotia a, Ashok K Science of The Total Environment Advances in decontamination of wastewater using biomass-based composites: A critical review *Science of The Total Environment* Volume 784, 25 August 2021,147108 <https://doi.org/10.1016/j.scitotenv.2021.147108>
45. Vítor J.P. Vilar, Cidália M.S. Botelho et.al; *Journal of Hazardous Materials*, Methylene blue adsorption by algal biomass based materials: Biosorbents characterization and process behaviour Volume 147, Issues 1–2, 17 August 2007, Pages 120-132 <https://doi.org/10.1016/j.jhazmat.2006.12.055>
46. Wan Mohd Aizat, Faridda Hannim Ahmad-Hashim et.al Valorization of mangosteen, “The Queen of Fruits,” and new advances in postharvest and in food and engineering applications: A review *Journal of Advanced Research* Volume 20, Pages 61-70 November 2019. <https://doi.org/10.1016/j.jare.2019.05.005>
47. Shuvodeep De a, Jesse Ji c et.al *Advances in bioenergy*, Biomass-derived composites for various applications volume 8, page 145-196, 2023 <https://doi.org/10.1016/bs.aibe.2023.01.001>
48. J.Jefferson Andrew et.al *Composites part c Sustainable biobased composites for advanced applications: recent trends and future opportunities – A critical review* volume 7 March 2022 100220, 2022 <https://doi.org/10.1016/j.jcomc.2021.100220>