

BIOCOMPOSITES: UNVEILING ITS POTENTIAL

“Biocomposites: A Review of Materials, Properties, and Applications for Sustainable Development.”

Or

"Biocomposites for a Sustainable Future: A Review of Natural Fiber Reinforcements, Matrices, and Applications"

Abstract

Composite materials are widely used in daily life in sectors such as automotive, aerospace, construction, and agriculture because of their durability, strength, and lightweight properties, and the composites market is expected to grow substantially in the coming years. However, synthetic composites cause environmental damage and health hazards, creating the need for eco-friendly and sustainable alternatives, among which biocomposites are considered a promising option. Biocomposites are composites in which at least one component, either the matrix or the reinforcement, is made from a renewable material, and they can be formed through combinations of natural fibres with non-biodegradable polymers, synthetic fibres with biopolymers, or natural fibres with biopolymers. Natural fibres, especially vegetable fibres, are widely used as reinforcement because they are renewable, readily available, and have a short growth period, while matrices may be petroleum-based or bio-based and help bind the fibres, transfer load, and protect the composite from damage. Biocomposites have applications in construction, automotive components, packaging, and agriculture, including slow-release fertilizer coatings, green herbicides, mulch films, plant pots, and soil conditioners. They also offer environmental benefits by reducing CO₂ emissions and promoting the use of renewable resources, though further research is needed to improve their structural and functional stability and to fully realize their potential as sustainable alternatives to conventional composites. ~~This review paper gives greater insights on biocomposites and its application~~ This review paper provides a comprehensive overview of biocomposites, including their composition, properties, and applications across multiple sectors. It further highlights current challenges related to mechanical performance, durability, and large-scale implementation, while identifying key research gaps and future directions for advancing sustainable material development.

Key words: Biocomposites, ~~Fibres, Composites~~ Natural fibres, Biopolymer, Sustainable materials, Green composites

Introduction

Composite materials are widely used in our daily life in various sectors like automotive, aerospace, construction, agriculture, etc. due to their durability, strength, and lightweight properties. Composites market grows at a Compound Annual Growth Rate (CAGR) of 8.2 per

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cent and also is expected to reach USD 150.28 billion by 2028 (Duggal, 2022). The expected outcome from the composites market clearly highlights the relevance of composites in elevating the status of the economy. Even though the composites have a wide range of applications, these materials cause environmental damage and severe health hazards. Most of the raw materials used for manufacturing composites produce carcinogenic substances upon heating. The use of synthetic resins and reinforcement materials such as glass and carbon fibers in the manufacture of composite materials causes lung disorders and skin allergy problems. The addition of additives like meta-phenylenediamine in the manufacture of composites also adversely affects the liver and kidney in human beings. Composite materials create environmental problems by creating large amounts of non-biodegradable waste and these composites take even longer years for chemical degradation (Sands et al., 2001). Apart from this, most of the composite raw materials are petroleum-derived products. Petroleum-based products are globally concerned due to their non-biodegradable and non-biocompatible nature, and also petroleum reserves are being depleted expeditious due to massive consumption worldwide (Raddadi and Fava, 2019). Considering all the negative impacts created by synthetic composites to our ecosystem, there arises a need for finding an eco-friendly and sustainable material to replace the synthetic types. Biocomposites can be considered as the best alternative materials to address these issues to ensure an eco-friendly and sustainable environment. This review aims to provide a comprehensive evaluation of biocomposites materials, focusing on their types, properties, and applications across various industries. Additionally, the study seeks to identify current limitations and research gaps, particularly in terms of structural performance, durability, and scalability, in order to guide future research and development in sustainable material science.

How/ what is the literature search methodology?

Add a section here to briefly explained the **Methodology of Literature Review**.

1. what approach was used to conduct this literature review?
2. where does the relevant publication identified from?
3. what key words were used?
4. what are the article selection criteria used ? (language, studies field (material properties, techniques, application), recency of the publication, relevancy to the review theme, scientific rigor, and contribution to the field)
5. how does the literature was organised? What are the themes used to organised the literature to enable structured analysis?

1. Biocomposites

Biocomposites are composites in which at least one component, either the matrix or the reinforcement, is derived from a renewable material. They can be made from three different

combinations, they are (i) Natural fibres (plant or animal fibres) and non-biodegradable polymers (duromers –for example, epoxy resin, phenolic resin and elastomers: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) (ii) Synthetic fibres and biopolymers (made by processing plants). (iii) Natural fibres and biopolymers. These composites are called green composites as they are less harmful to the environment (Djordjevic *et al.*, 2016).

2. Components of Biocomposites

Biocomposites are materials made from at least one component that comes from a biological source. For reinforcement, they often use plant fibers like cotton, flax, or hemp, as well as fibers from recycled wood, waste paper, or by-products from food crops. The matrix is usually a polymer, which is ideally made from renewable resources, but it can also be petroleum-based.

2.1. Natural fibres as composite reinforcement

Natural fibres are bio-based filaments that can be used instead of traditional fibre-reinforcing materials like glass (Patel *et al.*, 2021). They are usually grouped into three vegetable or plant fibres (cellulose), animal fibres (protein), and mineral fibres (Badamasi and Ibrahim, 2017). Among these, vegetable fibres are the most common because they grow quickly, are renewable, and are widely available. These fibres are made up of cellulose, hemicellulose, and lignin, and can be taken from sources like bast, leaves, seeds, fruits, wood, stalks, and grasses or reeds (Cicala *et al.*, 2010).

The typical life cycle of natural fibres includes extraction, processing, fabrication, use, disposal, and recycling. Several factors limit the large-scale production and application of these fibres. These limitations include variations in crop morphology and life cycles, the hydrophilic nature of fibres, and susceptibility to degradation by microorganisms and sunlight. The physical and chemical properties of natural fibres are influenced by plant source, climatic conditions, harvesting time, and the use of genetically modified organisms and fertilizers (Hodzic and Shank, 2014). A primary challenge in utilizing natural fibres is their low compatibility and poor wetting properties with most polymer matrices (García *et al.*, 2015). Fibres with a higher degree of polymerization, greater cellulose content, and a lower microfibrillar angle demonstrate increased tensile modulus and strength, making them preferable for green biocomposites fabrication (Gurunathan *et al.*, 2015).

2.1.1 Bast Fibres

Bast fibres are obtained from the outer cell layers of plant branches (Patel *et al.*, 2021). Common examples are jute, flax, hemp, banana, soybean, kenaf, and bamboo. These fibres are usually extracted through retting, which uses biological or chemical methods to break down plant stems. Bast fibres are known for their length and strength, and they have traditionally been used to make items such as bags, curtains, yarn, textiles, rope, and sacks (Ramesh *et al.*, 2017).

Jute is a widely used agro-fibre with a high tensile modulus, meaning it is stiff, and a low elongation at break, which measures how much it stretches before breaking. Jute's specific modulus, which is the elastic modulus divided by its mass density, is higher than that of glass

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fibre. Jute fibres also tend to be rough (Mohanty *et al.*, 2000). So, how does this have an impact to biocomposites from jute?

Researchers developed a fully biodegradable and edible nanocomposite using babul gum from *Acacia nilotica* (L.), reinforced with cellulose nanofibers from bamboo (Rose, 2019). They found that adding 10 per cent bamboo cellulose nanofibre increased the composite film's stiffness by 93 per cent. This increase in stiffness was linked to the high elastic modulus of bamboo fibre.

Flax fibres come from the outer layer of *Linum usitatissimum* stems. They are two to three times stronger than cotton fibres. Flax is used in wood-finishing products and can be woven into fabrics, which are then used to make composite materials with improved mechanical properties (Abhiram *et al.*, 2021).

Hemp comes from the *Cannabis sativa* plant and is grown for many industrial uses. It is used to make building materials, textiles, paper, plastics, and biofuel. Hemp has been used for about 50,000 years, especially for ship sails, nets, ropes, insulation, and caulking, because it is strong and resists saltwater. Henry Ford even built an entire car from hemp fibres (Mwaikambo, 2006).

Banana plants grow quickly, and fibres taken from their pseudo-stems are lignocellulosic. Composites made with banana fibre and unsaturated polyester have a specific modulus similar to glass fibre composites (Venkateshwaran and Elayaperumal, 2010). Sharma and Kumar (2013) found that banana fibre composites with 15 per cent fibre content had the best mechanical properties and could be used for structural applications like walls and roofs.

2.1.2 Leaf fibre

The coarse and hard fibres extracted from the leaf of the plant by hand scraping, after the beating/retting process or by mechanical extraction are called leaf fibres. Due to the relatively high strength, these fibres are mainly used for making woven ropes, fabrics, carpets, mats, etc. The typical leaf fibres are pineapple leaf fibre, sisal, palm, agave, etc. (Ramesh *et al.*, 2017). Sisal filaments are smooth, straight and yellow, which can be utilized for manufacturing rope, twine and brush bristles. Sisal is also utilised for upholstery, divider covers and custom floor coverings, which in turn gives intriguing surfaces to numerous interior structures (Mancinoa *et al.*, 2018)

Sisal fibre is a hard fibre extracted from the leaves of the sisal plant (*Agave sisalana*). The sisal leaf contains three types of fibres: mechanical, ribbon and xylem. The mechanical fibres are mostly extracted from the periphery of the leaf. They are roughly thickened-horse shoe shape and seldom divide during the extraction processes. They are the most commercially useful type of sisal fibres. Ribbon fibres occur in association with the conducting tissues in the median line of the leaf. Xylem fibres have an irregular shape and occur in opposite to the ribbon fibres through the connection of vascular bundles. They are composed of thin-walled cells and are therefore easily broken up and lost during the extraction process (Li *et al.*, 2000). Venkateshwaran *et al.*(2011) investigated the mechanical and moisture absorption behaviours of hybrid banana-sisal-epoxy composites. The banana-sisal-epoxy samples were fabricated with different fibre lengths (5, 10, 15, and 20 mm) and various weight percentages (8%,12%,

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16%, and 20%). Initially, the researchers identified the optimum banana fibre length and weight percentage of banana-epoxy composites. Then hybridization of sisal fibre in banana-epoxy composites up to 50 weight per cent was done, which in turn improved the mechanical properties and reduced the moisture absorption of the composites.

2.1.3. Seed /fruit fibre

Seed or fruit fibres are derived from the outer husk of plant fruits or seeds. Examples include cotton, kapok, rice husk, and milky weed floss. These fibres are primarily utilized in textile industries, water safety equipment, insulation materials, upholstery, and mattress products because of their softness and buoyancy (Ramesh *et al.*, 2017).

Alomayri *et al.* (2013) demonstrated that cotton fibres can serve as reinforcement in geopolymer composites. Increasing cotton fibre content up to 0.5 weight per cent enhanced both flexural ~~strength~~ strengths, defined as the material's ability to resist deformation under load, and fracture toughness, which describes resistance to flaw propagation under applied stress. However, increasing the cotton fibre content beyond 0.5 weight per cent reduced mechanical properties due to poor workability, leading to voids and fibre agglomerates. Additionally, the density of geopolymer composites decreased as fibre content increased.

Coir is a natural fibre extracted from coconut husk. Due to its high lignin content, coir exhibits greater durability compared to other natural fibres. Coir is considered a potential reinforcing material for various structural and non-structural applications (Verma *et al.*, 2013). Subramani (2012) compared coir fibre-reinforced bituminous mixes with conventional mixes and found that adding coir fibre to semi-dense bituminous concrete improved performance. The stability value increased by 1.3 times, resulting in greater stability under traffic loads.

2.1.4. Grass Fibers

Grass fibre is one of the important plant fibres that occur in different parts of plants, mainly in the stems and leaves. Grass fibres are lignocellulosic in nature, which consists of layers of lignin (outermost layer), hemicellulose (inner layer) and cellulose (innermost layer). Different grass fibres have varying proportions of lignin, hemicellulose, and cellulose (Kumar *et al.*, 2022). Jumaidin *et al.* (2019) conducted a study with cogon grass fibre reinforced with thermoplastic cassava starch matrix. The aim of this work was to study the effect of cogon grass fibre (CGF) on the water absorption, swelling and water solubility properties of the thermoplastic starch. When cogon grass fibre was reinforced with a thermoplastic cassava starch matrix, thickness, swelling, and water solubility of the composites decreased, suggesting improved dimensional and structural stability.

Haameem *et al.* (2016) conducted a study on the mechanical properties of a Napiergrass fibre-reinforced polyester composite. The study showed that 10 per cent alkali-treated Napier grass fibres yielded the highest strength compared with untreated grass fibres. It was also noted that the composite with a 25 per cent volume fraction of Napier fibre yielded the optimum tensile and flexural properties, i.e., tensile and flexural strength of the Napier fibre-reinforced polyester composite increased with increasing fibre volume fraction.

2.1.5. Wood fibres

Wood fibres are derived from a variety of tree species and are generally classified into two categories: softwood and hardwood. The primary distinction between these categories is that softwood fibres are longer than hardwood fibres (Ramesh *et al.*, 2017). Wood fibres comprise both living and non-living cells. Their composition is influenced by the location and age of the source tree. The hierarchical structure of wood fibres imparts superior performance characteristics, such as a high strength-to-weight ratio. Extraction methods for wood fibres from timber include chemical, mechanical, biological, and various combined processes (Dai and Fan, 2014).

Wood fibre composites are used extensively in construction, automotive, and infrastructure applications. A notable example in construction is the Tulou building, a distinctive rural dwelling in South China made with a wood fibre–clay composite. This composite structure demonstrates remarkable mechanical durability. For instance, after 1,240 years, the compressive strength of some Tulou walls remains as high as 30.17 MPa. This strength is attributed to wood fibre reinforcement. These buildings also provide superior environmental performance. Annual household energy consumption is only 2.43×10^4 MJ/y, which is significantly lower than that of other rural buildings in the region. Compared to modern cement buildings, Tulou structures provide enhanced thermal comfort for residents (Li *et al.*, 2012).

2.1.6. Biocomposites from agricultural waste

Okra (*Abelmoschus esculentus*) is a rich source of natural fibres. Large quantities of okra stems are discarded annually after harvesting, often without effective use. Okra bast fibre offers high cellulose content, strong mechanical properties and good thermal resistance, comparable to traditional bast fibres such as jute, hemp and ramie. Biocomposites reinforced with okra bast fibre can be produced using various matrices, including biodegradable corn starch, poly(lactic acid), poly(vinyl alcohol), and urea formaldehyde resin via different processing methods (Khan *et al.*, 2017).

Bagasse is one of the world's largest agricultural residues (Pandey *et al.*, 2000). Its main components are water, fibrous material and a small percentage of soluble solids (Walford, 2008). The composition varies with variety, maturity and harvesting methods. In addition to its use in ethanol production and as fuel for sugarcane mills, bagasse is increasingly used to produce composite materials for automotive vehicles, buses, and railway coaches. Enhancing mechanical properties such as flexural and tensile strength through improved manufacturing processes can further expand its applications (Rassiah *et al.*, 2012).

Merino *et al.* (2021) developed agricultural mulch films from industrial vegetable waste, specifically orange peels and spinach stems. Films were produced using hydrolysis at various durations (6, 16, and 24 hours) and temperatures (30, 50, and 70 °C). Hydrolysis at 30 °C for 24 hours resulted in films with optimal mechanical properties. In contrast, higher temperatures and longer treatment times produced materials with reduced mechanical strength and darker colouration. Applying a carnauba wax coating improved the films' water resistance

Even though every year tonnes of pineapple leaf fibres are being produced, only a small portion of it is being used in the field of feedstock and energy production. Pineapple leaf fibres can be used as reinforcement material for biocomposites. The fibre is white in colour and glossy like silk, medium length fibre with high tensile strength. It has a softer surface than other

natural fibres and maintains a good colour (Cherian *et al.*, 2011). Ambone *et al.* (2017) reported that waste leather buff (WLB) could be used as a reinforcement for the development of poly (lactic acid) composites, which was an alternative solution for the management of leather waste.

2.2. Matrices for biocomposites

The matrix is the continuous phase and plays an important role in determining the overall properties of the green composite. The principal purpose of a matrix is not as a load-carrying constituent but essentially to bind the fibres together. Moreover, it helps in transferring the load to the fibres and protects the composite. Each fibre must be separated from the other and uniformly coated by the matrix. Properties of the polymeric matrix govern the resultant properties of the polymeric composites. Thermal stability and temperature dependent properties and high temperature applications of a polymeric composite depend on its polymeric matrix (Singh *et al.*, 2017). The composite's shape, surface appearance, environmental tolerance and overall durability are dominated by the matrix, while the fibrous reinforcement carries most of the structural loads, thus providing macroscopic stiffness and strength. The polymer market is dominated by commodity plastics, with 80 per cent of materials based on non-renewable petroleum resources. Governments, companies and scientists are driven to find an alternative matrix to the conventional petroleum-based matrix through public awareness of the environment, climate change and limited fossil fuel resources. The matrices currently used in biofibre composites are biobased or ~~petroleum-based~~ petroleum-based plastics (Faruk *et al.*, 2012).

2.2.1. Petrochemical based matrices

Petrochemical based matrices are of two types: thermoplastics and thermoset matrices. Polypropylene (PP), polyethylene (PE), polystyrene (PS), and PVC (polyvinyl chloride) are used for the thermoplastic matrices. Thermoplastics are not widely used as a matrix for fibre composite materials because of their hydrophobic nature, high breaking elongation and high processing viscosity (Fowler *et al.*, 2006). Polyester, epoxy resin, phenol formaldehyde, and vinyl esters are used for the thermoset matrices, and they are the most widely used matrices for natural fibre reinforced polymer composites (Faruk *et al.*, 2012). The primary difference between thermoset and thermoplastic polymers is their behaviour in exposure to heat. Thermoplastics can be reheated, remoulded, and reprocessed into a new shape without any chemical changes, while thermosets that strengthen after heating cannot be remoulded or dissolved in a solvent (Murawski *et al.*, 2019)

2.2.2. Bio-based

As the world is looking for more ~~environmental~~ environmentally friendly products, there is a growing need to replace traditional polymer matrix materials with bioplastics in composites. Bioplastics are often made from renewable resources and can be produced in large amounts. They are usually low cost and biodegradable, which means they can break down naturally at the end of their life (Wei and McDonald, 2016). Some of the most common bio-based plastics available today include poly(ethylene terephthalate) (PET), polyethylene (PE), polypropylene (PP), polyamides (PA), poly(trimethylene terephthalate) (PTT), poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), poly(propylene carbonate) (PPC), thermoplastic starch (TPS),

soy protein-based resins, and other biodegradable polyesters such as poly(caprolactone) (PCL), poly(butylene succinate) (PBS), and poly(butylene succinate-co-adipate) (PBSA) (Mekonnen *et al.*, 2013).

3. Application of biocomposites

Biocomposites are being used in various field due to their performances over polymers composites prepared using artificial fibres. Major fields of application include manufacturing of automotive parts, building and construction, electrical and electronics industries, parts of agricultural equipment, packaging materials, biomedical and structural parts (Castro *et al.*, 2016).

3.1. Construction

The application of composites has been explored for both structural and non-structural purposes, with particular attention to their physical and chemical properties. Most synthetic composite materials used in construction have a significant negative environmental impact. In response, green and sustainable building design increasingly involves replacing cement, steel, and other conventional construction materials with green composites worldwide. Furthermore, there is a growing societal demand for greener buildings and for architects, designers, and engineers to deliver LEED-certified (Leadership in Energy and Environmental Design) primary structures (Saba *et al.*, 2017). Biocomposites can be utilized in the development of staircases, decks, elevator panels, and green fibre cabins. Christian and Billington (2011) evaluated the mechanical performance of eco-friendly materials composed of cellulose and polyhydroxybutyrate combined with hemp fibres. These composites demonstrated mechanical properties comparable to those of structural wood, suggesting their suitability for flooring, scaffolding, walls, and temporary construction. Natural fibres such as coconut, sisal, banana, hemp, sugarcane, and cotton are frequently used to reinforce polymer systems, thereby enhancing specific properties of the final product. Cellulosic fibres as reinforcement for various matrices represent a significant option for the construction industry (Sanchez *et al.*, 2018). Saba *et al.* (2016) investigated the fabrication of kenaf/epoxy hybrid nanocomposites incorporating oil palm nanofiller. The resulting hybrid nanocomposites exhibited improved mechanical and morphological properties, indicating potential applications in both structural and semi-structural building materials. These composites also have the potential to replace traditional construction materials such as steel, aluminium, ceramic bricks, wood, cement, aggregates, cladding, and partitioning materials in the development of sustainable green buildings.

3.2. Automotive industry

In recent decades, the adoption of natural fibre and green composites has significantly transformed the automotive sector by reducing reliance on non-renewable, costly materials (Koronis *et al.*, 2013). However, the use of natural fibre composites in automotive applications dates back to the 1940s. In 1942, Henry Ford introduced the first prototype composite car constructed from hemp fibre (Rusu *et al.*, 2011). During the 1950s, the East German Trabant featured a body made from composites containing natural fibres. The subsequent development of petrochemical-based polymers rendered this green technology economically unviable, leading to its decline in the automotive industry. The oil crisis of the 1970s renewed interest in

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What are the research gaps between biocomposites and the application field?

Does the biocomposite have any industrial relevance in respective application?

natural fibre composites, and by the 1980s, automotive door panels composed entirely of bio-based natural fibres and bio resins were developed. In the 1990s, Daimler-Benz pioneered the integration of natural fibres in commercial vehicles through the 'Belem' project in the Amazon delta, South America. By the late 2000s, natural fibre composites had become a prominent concept in advanced automotive design (Akampumuza *et al.*, 2017). The automotive industry now incorporates green composites in both internal and external components (Yildiz *et al.*, 2019). These composites, derived from renewable materials, are utilized in various car-body parts such as dashboards, door panels, parcel shelves, seat cushions, and linings (Peças *et al.*, 2018). The current trend toward electric vehicle production emphasizes the importance of lightweight materials for chassis construction to optimize battery performance (Velandia *et al.*, 2019). Green composites offer reduced energy consumption and enhanced vibration damping in transportation and automotive sectors due to their lower weight compared to steel and iron components, which is also advantageous in shipbuilding and mass transit. Composite structural parts are fuel-efficient, ~~environmental~~environmentally friendly due to lower carbon dioxide emissions, and more flexible than metal, allowing for diverse moulding and design possibilities (Saba *et al.*, 2017). However, their water absorption properties limit their use in wet glass fibre reinforced polymer (GFRP) applications, such as kayaks, piping, tanks, and boats (Dicker *et al.*, 2014).

3.3. Packaging

Billions of tonnes of petroleum products are used to produce plastic bags, which can be saved for future use, as these energy resources are not recyclable. This is the area where a large amount of nondegradable waste has been created. Biopolymer-based biodegradable food packaging materials could potentially replace non-biodegradable plastics (Tang *et al.*, 2012). Mohanty *et al.* (2014) conducted a study on chemically modified date palm leaf (DPL) using acrylic acid. Prepared biocomposites reinforced with 26 weight per cent DPL fibre loading showed promising features as water and chemical resistant hydrophobic packaging materials.

Nazrin *et al.* (2020) studied the incorporation of nanocellulose to enhance the properties of thermoplastic starch (TPS), polylactic acid (PLA) and polybutylene succinate (PBS) for food packaging. It was reported that the addition of nanocellulose in TPS improved the low water barrier and tensile properties, while the addition of nanocellulose into PBS and PLA enhanced the oxygen barrier properties and mechanical strength.

Teabags are commonly made of filter paper or food-grade plastic, or occasionally of silk cotton or silk. Teabag filter paper can be made with a blend of wood and vegetable fibres, such as bleached pulp of abaca, hemp etc. Heat-sealed tea bag paper is made with heat-sealable thermoplastic, such as polyvinyl chloride or a biocomponent fibre, on the inner side of the teabag surface (Fisher, 2020).

3.4. Agriculture

Biocomposites are used as coating material in slow-release fertilizers for agriculture. Sofyane *et al.* (2021) found that fertilizers based on starch acetate, glycerol, and polyvinyl alcohol biocomposites improved fertilizer use efficiency. A study conducted by Kottegoda *et al.* (2011) noted that urea-modified hydroxyapatite nanoparticles were incorporated into *Gliricidia sepium* wood, resulting in a fertilizer with slow and sustained urea release and enhanced efficiency. Urea fertilizer coated with starch-grafted rubber was also developed as a polymer membrane for controlled urea release. This core-shell structure, with a hydrophilic starch core and hydrophobic polymer shell, exhibited low swelling nature and is suitable for encapsulating water-soluble fertilizers such as urea (Riyajan *et al.*, 2012).

Biocomposites are also used to produce biodegradable mulch films. Menossi *et al.* (2021) reported that the biodegradability of these films can be tailored to the crop season, providing effective pest and weed management and supporting high yields. Chaiphut *et al.* (2021) developed a biocomposites film from a blend of poly(lactic acid) and polybutylene succinate with lemon grass powder as a natural filler. The addition of the filler improved the film's light barrier properties, allowing it to absorb over 90 per cent of both UV and visible light, making it suitable for weed prevention. Moreno and Moreno (2008) found that biodegradable mulch films warm soil less than polyethylene mulches, which is beneficial in hot climates and has less negative impact on soil microbial activity. Viscusi *et al.* (2022) observed complete inhibition of *Cynodon dactylon* weed growth after 12 days using a biocomposites film containing 20 per cent rice milk-based beads and chilli powder extract.

Biodegradable plant pots and trays made from biocomposites are suitable for seedlings and young plants. These pots can be planted directly in the soil, reducing transplant shock and minimizing plastic waste. Sun *et al.* (2018) found that flower pots made from straw fiber-reinforced hydrolyzed soy protein isolate, urea, and formaldehyde composites offer good thermal and mechanical properties, biodegradability, and low cost. Treinytea *et al.* (2014) reported that pots made from starch, rapeseed cake, crude glycerol, and urea had half the water evaporation rate and lower soil temperature fluctuations compared to commercial peat pots.

Biocomposites materials are used to produce erosion control products such as blankets, mats, and logs. These products stabilize soil, prevent erosion, and support vegetation growth on slopes. Oil palm empty fruit bunch and wild seaweed serve as reinforcement and matrix, respectively, in biocomposites designed for erosion control during land clearing or replanting (Ashikin *et al.*, 2019).

Cannazza *et al.* (2014) developed cellulose-based superabsorbent hydrogels as an environmentally friendly alternative to acrylate-based hydrogels. Using derivatives of carboxymethyl cellulose sodium salt and hydromethyl cellulose, they synthesized hydrogels with swelling, water retention, and soil conditioning properties comparable to acrylate-based products. Field studies showed that applying these cellulose-based hydrogels can reduce water consumption by up to 50 per cent without affecting plant growth or yield.

3. Conclusion

Growing awareness and increasing demand in society towards a sustainable and pollution free environment drive the material science and technology to manufacture the commercial

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What does the reader get from the review?

What is the future direction of biocomposites?

What is the impact from this review?

products that are fully biodegradable and compatible with the environment. Fully green or biocomposites is a response to the growing demand for greener, renewable products, and it opens new opportunities and avenues for both academicians and industries to manufacture sustainable products with attributes such as stiffness, high strength, renewability, biodegradability, durability, etc. Even though biocomposites has wide range of applications in our daily life, which opens a door to a greener and sustainable future, more research has to be carried out in this field to exploit its full potential

Example of my suggested conclusion based from the manuscript content:

Biocomposites represent a promising class of sustainable materials that is capable of addressing the environmental and health concerns associated with conventional composites. This review highlights versatility across multiple applications and industries, supported by renewable resources and reduced environmental impact.

Nonetheless, key challenges still remain which includes variability in natural fibre properties, moisture sensitivity, and limitations in long-term durability and scalability. To address these issues requires advancements in fibre modification, matrix development, and processing technologies. Therefore, future research should focus on developing high-performance, standardized, and cost-effective biocomposites to enable broader industrial adoption. Overall, biocomposites hold significant potential in driving the transition toward sustainable material systems.

References

- Abhiram, Y., Das, A., and Sharma, K. K. 2021. Green composites from natural fibres and biopolymers: A review on processing, properties and applications. *J. Reinf. Plast.* 41(13-14): 2658-2664.
- Akampunguza, O., Wambua, P. M., Ahmed, A., Li, W., and Qin, X. H. 2017. Review of the applications of biocomposites in the automotive industry. *Polym. Compos.* 38(11): 2553-2569.
- Alomayri, T., Shaikh, F. U. A., and Low, I. M. 2013. Characterisation of cotton fibre- reinforced geopolymer composites. *Compos.Eng.* 50: 1-6.
- Ambone, T., Joseph, S., Deenadayalan, E., Mishra, S., Jaisankar, S., and Saravanan, P. 2017. Polylactic acid (PLA) biocomposites filled with waste leather buff (WLB). *J. Polym. Environ.* 25: 1099-1109.
- Ashikin, N. S. S. N., Djalaluddin, A., Yusuff, S., Khalil, H. A., and Syakir, M. I. 2019. Empty fruit bunch-seaweed biocomposite as potential soil erosion mitigation material for oil palm plantation. *Bio. Resour. Technol.* 14(3): 5438-5450.
- Badamasi, H. and Ibrahim, A. 2017. Development and characterization of bio-composite: A review. In: *2nd International Conference on Green Engineering for Sustainable Development (IC-GESD 2017)*, Bayero University, Kano, Nigeria, p.4.
- Cannazza, G., Cataldo, A., Benedetto, E., Demitri, C., Madaghiele, M., and Sannino, A. 2014. Experimental assessment of the use of a novel superabsorbent polymer (SAP) for the optimization

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For a good review, make sure the references are not more than 150 references.

of water consumption in agricultural irrigation process. *Water* 6(7): 2056-2069.

Castro, E. A., Franco, F. I., Samsudin, H., Fang, X., and Auras, R. 2016. Poly (lactic acid) mass production, processing, industrial applications and end of life. *Adv. Drug Deliv. Rev.* 107: 333-366.

Chaiphut, M., Ross, S., Ross, G., Suphrom, N., and Mahasaranon, S. 2021. Influence of the lemongrass powder and polybutylene succinate on the properties of biocomposite films based on poly (lactic acid). *Materials Today: Proceedings* 47(3): 3537-3545.

Cherian, B. M., Leão, A. L., Souza, S. F., Costa, L. M. M., Olyveira, G. M., Kottaisamy, M., Nagarajan, E. R., and Thomas, S. 2011. Cellulose nanocomposites with nanofibres isolated from pineapple leaf fibers for medical applications. *Carbohydr. Polym.* 86(4): 1790-1798.

Christian, S. J. and Billington, S. L. 2011. Mechanical response of PHB and cellulose acetate natural fiber-reinforced composites for construction applications. *Compos. Eng.* 42(7): 1920–1928.

Cicala, G., Cristaldi, G., Recca, G., and Latteri, A. 2010. Composites based on natural fibre fabrics. In: Dubrovski, P. D. (ed.), *Woven Fabric Engineering*. Intech Publishers, UK, 436p.

Dai, D. and Fan, M. 2014. Wood fibres as reinforcements in natural fibre composites: structure, properties, processing and applications. In: *Natural Fibre Composites*, Woodhead Publishing, pp.3-65. [On-line]. Available: <https://doi.org.10.1533/978085709928.1.3> [03rd October 2023].

Djordjevic, Z., Jovanovic, S., Gavrilovic, O., Catic, D., and Savic, S. 2016. Biocomposites - ecologically acceptable materials. In: *1st International Conference on Quality of Life, Kragujevac, Serbia, June* (pp. 9-10).

Dicker, M. P. M., Duckworth, P. F., Baker, A. B., Francois, G., Hazzard, M. K., and Weaver, P. M. 2014. Green composites: A review of material attributes and complementary applications. *Compos. Appl. Sci.* 56: 280–289.

Duggal, P. 2022. Composites Market in 2028. *Compos. –B: Eng.* 50: 1-6

Eichhorn, S. J., Baillie, C. A., Zafeiropoulos, N., Mwaikambo, L. Y., Ansell, M. P., Dufresne, A., Entwistle, K. M., Franco, P. J. H., Escamilla, G. C., Groom, L., Hughes, M., Hill, C., Rials, T. G., and Wild, P. M. 2001. Review: Current international research into cellulosic fibres and composites. *J. Mater. Sci.* 36(9): 2107-2131.

Faruk, O., Bledzki, A. K., Fink, H. P., and Sain, M. 2012. Biocomposites reinforced with natural fibers. *J. Polym. Sci.* 37(11):1552-1596.

Fisher, G. 2020. Demand for sustainable packaging and materials is catching on. *Int. Fiber j.* 79 (3) :12-15

Fowler, P. A., Hughes, J. M., and Elias, R. M. 2006. Biocomposites: Technology, environmental credentials and market forces. *J. Sci. Food Agric.* 86(12): 1781- 1789.

García, G. D., Carbonell, A., Samper, M. D., Sanoguera, D. G., and Balart, R. 2015. Green composites based on polypropylene matrix and hydrophobized spend coffee ground (SCG) powder. *Compos. Eng.* 78: 256-265.

- Gurunathan, T., Mohanty, S., and Nayak, S. K. 2015. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Compos. Appl. Sci.* 77: 14-19.
- Haameem, J. A. M., Majid, M. S. A., Afendi, M., Marzuki, H. F. A., Fahmi, I., and Gibson, A. G. 2016. Mechanical properties of napier grass fibre / polyester composites. *Compos. Struct.* 136: 8-10.
- Hodzic, A. and Shanks, R. 2014. *Natural fibre composites: materials, processes and properties*, Woodhead Publishing, Oxford, UK, ISBN 0857099221.
- Jumaidin, R., Saidi, Z. A. S., Ilyas, R. A., Ahmad, M. N., Wahid, M. K., Yaakob, M. Y., Maidin, N. A., Rahman, A. M. H., and Osman, M. H. 2019. Characteristics of cogon grass fibre reinforced thermoplastic cassava starch biocomposite: Water absorption and physical properties. *Exp. Therm. Fluid Sci.* 62(1): 43-52.
- Khan, G. M. A., Yilmaz, N. D., and Yilmaz, K. 2017. Okra fibers: Potential material for green biocomposites. In: *Green Biocomposites* [On-line]. Available: https://doi:10.1007/978-3-319-49382-4_12 [24th September 2023].
- Koronis, G. and Silva, A. 2018. Green composites reinforced with plant-based fabrics: cost and eco-impact assessment. *J. Compos. Sci.* 2(1): 8-13.
- Koronis, G., Silva, A., and Fontul, M. 2013. Green composites: a review of adequate materials for automotive applications. *Compos. Eng.* 44(1): 120-127.
- Kottegoda, N., Munaweera, I., Madusanka, N., and Karunaratne, V. 2011. A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. *Curr. Sci.* 63(2) : 73-78.
- Kumar, H., Jaiswal, D., and Jena, H. 2022. A state of art review on grass fibre reinforced polymer composite. *IOP Conf. Ser: Mater. Sci. Eng.* 1258(1): 3-6.
- Li, Q., Sun, X., Chen, C., and Yang, X. 2012. Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study. *Energy Build.* 49: 317-326.
- Li, Y., Mai, Y. W., and Ye, L. 2000. Sisal fibre and its composites: A review of recent developments. *Compos. Sci. Technol.* 60(11): 2037-2055.
- Mancinoa, A., Marannano, G., and Zuccarello, B. 2018. Implementation of eco- sustainable biocomposite materials reinforced by optimized agave fibers. *Struct. Integr.* 8: 526-538.
- Mekonnen, T., Mussone, P., Khalil, H., and Bressler, D. 2013. Progress in bio-based plastics and plasticizing modifications. *J. Mater. Chem. A.* 1(43): 13379-13398.
- Menossi, M., Cisneros, M., Alvarez, V. A., and Casalongue, C. 2021. Current and emerging biodegradable mulch films based on polysaccharide bio-composites. A review. *Agron. Sustain. Dev.* 41(4): 4-9.
- Merino, D., Simonutti, R., Perotto, G., and Athanassiou, A. 2021. Direct transformation of industrial vegetable waste into bioplastic composites intended for agricultural mulch films. *Green Chemistry* 23(06): 5956-5971.
- Mohanty, A. K., Misra, M. A., and Hinrichsen, G. I. 2000. Biofibres, biodegradable polymers

and biocomposites: An overview. *Macromolecular Mater. Eng.* 276 (1): 1-24.

Mohanty, J. R., Das, S. N., Das, H. C., and Swain, S. K. 2014. Effect of chemically modified date palm leaf fiber on mechanical, thermal and rheological properties of polyvinylpyrrolidone. *Fibers Polym.* 15: 1062–1070.

Moreno, M. M., and Moreno, A. 2008. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. *Sci. Hortic.* 116(3): 256-263.

Murawski, A., Diaz, R., Inglesby, S., Delabar, K., and Quirino, R. L. 2019. Synthesis of bio-based polymer composites: Fabrication, fillers, properties, and challenges. *Mater. Sci.* [On-line]. Available: doi.10.1007/978-3-030-04741-2_2 [28th September 2023].

Mwaikambo, L. 2006. Review of the history, properties and application of plant fibres. *African J. Sci. Technol. Innov. Dev.* 7(2): 4-6.

Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Syafiq, R., and Sherwani, S. F. K. 2020. Nanocellulose reinforced thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications. *Front. Chem.* 8(213): 8-10.

Pandey, A., Soccol, C. R., Nigam, P., and Soccol, V. T. 2000. Biotechnological potential of agro-industrial residues. I: Sugarcane bagasse. *Bioresource Technol.* 74(1):69–80.

Patel, P., Gohil, P., and Parmar, V. 2021. Bio composite material: Review and its applications in various fields. In: *Encyclopedia of Materials: Composites*, Elsevier, Amsterdam pp. 80-93.

Raddadi, N. and Fava, F. 2019. Biodegradation of oil-based plastics in the environment: existing knowledge and needs of research and innovation, *Sci. Total Environ.* 679: 148-158

Ramesh, M., Palanikumar, K., and Reddy, K. H. 2017. Plant fibre based bio-composites: Sustainable and renewable green materials. *Renewable Sustain. Energy Rev.* 79(18): 558–584.

Rassiah, K., Nagapan, S. R. M. J., and Jidin, R. M. 2012. The effect of sodium hydroxide (NaOH) on water absorption and biodegradability of low density polyethylene (LDPE)/sugarcane bagasse (SCB) composites. In: Rakesh, P. K. and Singh, I. (eds), *Processing of green composites*. Springer, 142p. [On-line]. Available: <https://doi.org/10.1007/978-981-13-6019-0>.

Riyajan, S. A., Sasithornsonti, Y., and Phinyocheep, P. 2012. Green natural rubber-g- modified starch for controlling urea release. *Carbohydr. Polym.* 89(1): 251-258.

Rose, J. M. 2019. *Development and characterization of natural gum base Nanocomposite*. Ph.D. thesis, Kerala Agricultural University, Thrissur 120 p.

Rusu, D., Boyer, S., Lacrampe, M. F., and Krawczak, P. 2011. Bioplastics for automotive applications. In: Pilla, S. (ed.), *Bioplastics and biocomposites engineering applications*, Wiley Publishers, 397 p.

Saba, N., Jawaid, M., Sultan, M. T. H., and Alothman, O. Y. 2017. Green biocomposites for structural applications. In: *Green biocomposites: Design and applications*, Springer International Publishers. doi.org.10.1007/978-3-319-49382-4

Saba, N., Paridah, M. T., Abdan, K., and Ibrahim, N. A. 2016. Effect of oil palm nano filler on mechanical and morphological properties of kenaf reinforced epoxy composites. *Constr. Build. Mater.* 123: 15-26

Sands, J.M., Fink, B.K., McKnight, S.H., Newton, C.H., Gillespie Jr, J.W., and Palmese, G.R.

2001. Environmental issues for polymer matrix composites and structural adhesives. *Clean. Prod. Process.* 2:228-235.
- Sanchez, S. E. L., Aldureid, A., and Lagar, J. M. 2018. Biocomposites of different lignocellulosic wastes for sustainable food packaging applications. *Compos. Eng.* 145: 215–225.
- Sharma, N. K. and Kumar, V. 2013. Studies on properties of banana fiber reinforced green composite. *J. Reinf. Plast. Compos.* 32(8): 525–532.
- Singh, A. A., Afrin, S., and Karim, Z. 2017. Green composites: Versatile material for future. In: *Green Biocomposites: Design and Applications*, Springer Publishers, 29-44. [On-line]. Available: https://doi.org/10.1007/978-3-319-49382-4_2
- Sofyane, A., Ablouh, E., Lahcini, M., Elmeziane, A., Khouloud, M., Kaddami, H., and Raihane, M. 2021. Slow-release fertilizers based on starch acetate/glycerol/polyvinyl alcohol biocomposites for sustained nutrient release. *Materials Today* 36(01): 74-81.
- Subramani, T. 2012. Experimental investigations on coir fibre reinforced bituminous mixes. *Int. J. Civ. Struct. Environ. Infrastruct. Eng. Res. Dev.* 7(3): 4-5.
- Sun, E., Liao, G., Zhang, Q., Qu, P., Wu, G., Xu, Y., Yong, C., and Huang, H. 2018. Green preparation of straw fiber reinforced hydrolyzed soy protein isolate / urea formaldehyde composites for biocomposite flower pots application. *Mater.* 11(9): 12-15
- Tang, X. Z., Kumar, P., Alavi, S., and Sandeep, K. P. 2012. Recent advances in biopolymers and biopolymer-based nanocomposites for food packaging materials. *Crit. Rev. Food Sci. Nutr.* 52(5): 426-442.
- Treinytea, J., Grazuleviciene, V., Bridziuviene, D., and Svediene, J. 2014. Properties and behaviour of starch and rapeseed cake based composites in horticultural applications. *Est. J. Ecol.* 63 (1): 15–27.
- Velandia, J. E. V., Falco, D. G., Walter, A. C. S., Cavaliero, C. K. N., and Seabra, J. E. A. 2019. Life cycle assessment of electric vehicles and buses in Brazil: Effects of local manufacturing, mass reduction, and energy consumption evolution. *Int. J. Life Cycle Assess.* 24(10): 1878-1897.
- Venkateshwaran, N. and Elayaperumal, A. 2010. Banana fiber reinforced polymer composites – A review. *J. Reinf. Plast. Compos.* 29(15): 2387–2396.
- Venkateshwaran, N., Elayaperumal, A., Alavudeen, A., and Thiruchitrambalam, M. 2011. Mechanical and water absorption behaviour of banana / sisal reinforced hybrid composites. *Mater. Des.* 32(7): 4017-4021.
- Verma, D., Gope, P. C., Shandilya, A., Gupta, A., and Maheshwari, M. K. 2013. Coir fibre reinforcement and application in polymer composites. *J. Mater. Environ. Sci.* 4(2): 263-276.
- Viscusi, G., Lamberti, E., Aquino, G., Rodriquez, M., and Gorrasi, G. 2022. Fabrication of novel biocomposites based on rice milk for the delivery of capsaicinoids as green herbicides against *Cynodon Dactylon* weed. *Crystals* 12(8): p.1048.
- Walford, S. N. 2008. Sugarcane bagasse: how easy is it to measure its constituents?. In: *Proceedings of the Annual Congress-South African Sugar Technologists' Association.* 29-31 July 2008, South African Sugar Technologists Association, Mount Edgecombe, South Africa pp. 266-273.

Wei, L. and McDonald, A. G. 2016. A review on grafting of biofibers for biocomposites. *Mater.* 9(4): 7-9.

Yang, Y., Boom, R., Irion, B., Heerden, D. J. V., Kuiper, P., and Wit, H. D. 2012.

Recycling of composite materials. *Chem. Eng. Process.* 51: 53– 68 Yildiz, C., Ankaya, S., and

Sezen, B. 2019. Effects of green supply chain management practices on sustainability performance. *J. Manuf. Technol. Manag.* 30(1): 98– 125

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