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REVIEW ARTICLE

A review of environmental friendly green composites: production methods, current progresses, and challenges

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Abstract

The growing concern about environmental damage and the inability to meet the demand for more versatile, environmentally friendly materials has sparked increasing interest in polymer composites derived from renewable and biodegradable plant-based materials, mainly from forests. These composites are mostly referred to as "green" and they can be widely employed in many industrial applications. Green composites are less harmful to the environment and could be potential substitutes for petroleum-based polymeric materials. It is helpful to limit usage of fossil oil assets by developing biopolymer matrices such as cellulose-reinforced biocomposites using renewable assets such as plant oils, carbohydrates, and proteins. This paper focuses on green composites processing utilizing a variety of naturally available resources, sustainable materials which are not detrimental to the environment, new scientific signs of progress in achieving green sustainable development, as well as nanotechnology and its environmental consequences. Additionally, the environmental impacts of different composite materials are examined in this paper, along with their production from eco-friendly materials. Moreover, the manufacturing aspects of green composites and some concerns related to their production are also discussed. The merits of green composite materials and valid reasons why they are a valuable substitute for the traditionally used composite materials are also covered.

Keywords Green · Organic · Inorganic reinforcement · Biocomposites

Introduction

Green sustainability, in a more profound sense, is the wonderment of human civilization. Energy and environmental conservation are critical to the survival of the human race today. One of the most urgent requirements of the moment is efficient sustainability. Technology and science are at a crossroads regarding ecological, energy, and green sustainability. The necessities of human society, fuel, power, and water, have engulfed scientific vitality and complexity in recent years. Science and technological brilliance today is rich with foresight and patience. On a global scale, the United Nations Conferences in Rio de Janeiro (1992) and Johannesburg (2002) altered and elevated futuristic terminology as a focal point for discourse. There has been a worldwide blossoming of environmental ideas, and the word "green" has been associated with many interpretations since the 1980s. A green composite, in general, is a material developed wholly of renewable materials or a combination of synthetic and biologically based materials at a specific ratio. Moreover, by periodically including renewable resources in the composition of the composite, the entire composite could be deemed "green" contributing towards a potentially sustainable use in terms of material consumption and energy efficiency. Today, the ambition and challenge of environmental sustainability are altering scientific and engineering concepts and technologies. The goals of scientific strategies in undeveloped nations regarding the environment and energy are being re-examined and contemplated with a more positive perspective related to sustainability.

The perception of the people regarding what constitutes an environmentally friendly product or material have begun to vary substantially. One reason to associate the changes in perspective with this period is the introduction in 1990 of the BRE environmental assessment method, a method developed by the Building Research Establishment to measure the

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sustainability of contemporary commercial buildings. Since then, over 260 similar grading systems have been created around the world (Costello and Bischel 2013). Since buildings utilize roughly 40% of all raw materials spent globally (Cheng et al. 2008), and modern construction activity creates approximately 40% of non-residential waste, the environmental quality of materials and products is often an integral part of such systems (ElSorady and Rizk 2020). Several rating systems, like the Leadership in Energy and Environmental Design (LEED) for operations and maintenance of the US Green Building Council, have gone even farther, requiring the use of recyclable sources in building operations (ElSorady and Rizk 2020). Adams (2019) explained the green environment and the importance of environmental sustainability in developing nations. The authors of this disquisition addressed the beginnings of environmental sustainability, the predicament of modern sustainable development, mainstream environmental sustainability, rebuttal in sustainable development, sustainable forest areas, sustainability and river regulation, and green development reform movements or radicalization. Due to urbanization and technical breakthroughs in various industries, large amounts and numerous types of industrial waste (Fernando and Claudio 2020) have been generated by industry, mining, farming, and domestic activities. As a consequence, the management of waste is now one of the most challenging environmental concerns of the world. With increased environmental awareness, a scarcity of landfill space, and a massive dumping cost, recycling by-products, and solid waste have become a viable alternative to disposal. For instance, using recycled waste materials in the construction industry may improve the physical and mechanical characteristics, durability performance, and microstructure of cement concrete, which are difficult to achieve using only raw materials (Putman and Amirkhanian 2004; Batayneh et al. 2007).

Every year, about 100 million stacks of fibre are consumed around the world. Natural fibers have several advantages over conventional fibers, including lower cost, lower density, reusability, and good biocompatibility (Baley 2002). Non-biodegradable material recycling is quite challenging. The exploitation of natural resources, large-scale industrial waste products, and industrial pollution necessitates the creation of novel and suitable solutions for long-term growth (Cong 2018). To render them affordable, sustainable, and eco-friendly, many studies have suggested developing biodegradable green composites utilizing renewable sources such as natural fibers, agro-feedstock, and biodegradable polymers. Additionally, such green composites, which are mostly made up of natural fibers and biopolymers, have superior mechanical properties, notable manufacturing advantages, relatively low density, and are biodegradable, making them suitable for industrial use (Ghorbal et al. 2019; Wang et al. 2017; Lima et al. 2020). Although green composites have the potential to replace synthetic polymeric materials shortly, they have already been employed in applications such as packaging, horticultural products, automobile panels, and furniture. (Adekomaya 2020). According to an article in Science Daily, 24 trillion pieces of microplastics are found in the ocean (Science Daily 2021).

Researchers have become increasingly interested in developing biodegradable materials for more than a decade, and many biopolymers have indeed been produced and are often used in various industries. Composites, as versatile materials with outstanding qualities, have a wide range of applications in sectors such as automobiles, aviation, and shipping (Amjad et al. 2021; Husein et al. 2021). Concerns over the ecological consequences of composites with two or more ingredients have grown in the last decade. Green composites have been created to create composites that are environmentally beneficial (Kazak et al. 2017). Most are either entirely biodegradable or moderately biodegradable. Recent advances in the production of biodegradable green composites, such as starch and bamboo fiber-based composites, as well as soy protein-based composites with natural fibers, have shown comparable qualities (Kim et al. 2022; Yusof et al. 2019; Nkeuwa et al. 2022). The ever-increasing amount of plastic and composite debris, as well as contamination, has boosted environmental awareness among customers, public officials, and producers. The current pace of fossil fuel consumption has been determined to be 1 lakh times the rate it is formed by nature, which would be unsustainable (Stevens 2002). To address these environmental issues, governments around the world enacted legislation encouraging the use of recycled bio-based sustainable materials (Nir et al. 1993). Green composite materials have sparked a resurgence of curiosity in numerous applications spanning aerospace to consumer products in the last two decades or more (Al Kiey and Hasanin 2021). Various drivers are thought to have played a role in the rebirth. Nonetheless, two major influences appear to have emerged: environmental and economic factors. The hunt for new and more “environmentally friendly” materials and goods is sparked by growing awareness about the impact of our activities on the environment. The utilization of scrap, reused, or reclaimed resources is an intermediary position regarding the environmental profile of green composite materials. In their paper, Puttegowda et al. (2018) have outlined in great detail the potential of natural/synthetic hybrid composites for aerospace applications. Blending waste fiber from recycled wood or newsprint with post-industrial or post-consumer polymers like polyethylene or polypropylene to create a “hybrid” natural-synthetic composite has several benefits (Pickering et al. 2016; Hayajneh et al. 2021). This review paper will focus on the processes used to create green composites from various raw materials that are friendly to the environment, as well as the most recent developments and issues surrounding green composites that are sustainable and benign to the environment. The importance of nanotechnology and the effects its products have on the environment are also covered in this paper. There is also discussion on the importance of waste recovery, recycling, reuse, and material sustainability.

Green composites manufacturing

Non-degradable polymeric resins, in conjunction with high tensile strength fibers like aramids, graphite, and glass, are being used to produce the most commercially available composite materials. These materials are generally used in situations requiring a high level of strength, rigidity, and lifetime. Most of the resins and fibers utilized in these composite materials are petroleum-based. Since the quantity of large-volume productions like aircraft and civilian constructions has grown, green production and life-cycle evaluations have made ecologically safe composites a priority. The amount of large-volume output like aircraft and civilian construction has risen. Composite materials cannot be recycled or reused because they consist of two separate segments bound together and have a definite form. Currently, well over 90% of the composites are dumped in landfills. These may well not decay for extensive periods in landfills, rendering the ground useless for some other purpose. A resin composition obtained from biological material is referred to as a bio-resin (Georgios et al. 2016). It is also often used to refer to resin compositions that are only partially sourced from biological sources. Plant oils, polysaccharides (mostly cellulose and glucose), and proteins are the most extensively used sustainable resources (Laine and Rozite 2010; Raquez et al. 2010). Natural oils as antecedents for resin systems were investigated in the last century due to the production of oilseed plants for edible purposes. Rapeseed, soybean, castor, pine, and other plant oils have been employed (Laine and Rozite 2010).

Naturally derived fibers are typically categorized according to their source, whether animal, plant or mineral-based. Natural fibers are derived from various plant elements, and all these raw materials are widely used in the production of green composites (Robson et al. 1993). Mwaikambo and Ansell (2002) divided these plant or vegetable fibers into categories based on their source (e.g., stem (bast) fibers, fruit, or seed fibers, leaf fibers) (Bledzki and Gassan 1999). Van Voorn et al. (2001) estimate that a minimum of a thousand different types of plants produce usable fibers. Natural fibers derived from plants are mainly widely distributed in tropical climates but can also be seen in terrestrial forests. Plant fibers are considered environmentally beneficial because they are biodegradable and renewable (Das and Chakraborty 2008; John and Anandjiwala 2008). For instance, natural fibers are used in the paper, textile, bioenergy industries, etc., because of their overall qualities (Ozturk et al. 2020). Natural fiber-reinforced composites are getting popular due to their convenience of use, reusability, low density, and low price. (Dong 2018). Natural fibers, including bamboo, banana, jute, hemp, kenaf, and sisal, have been used as reinforcing materials for an extended period. Organic fibers like wheat, sisal, bamboo, banana, jute, cotton, flax straw, silk, sugarcane, oil palm, and coconut have also acquired popularity in producing advanced technology products. (Fowler et al. 2006; Christian and Billington 2009). The use of adequate technical approaches, such as thermoforming (TF), pultrusion, injection molding, compression molding (CM), and resin transfer molding (RTM), is by far the most significant part of composite manufacture (Hofmann et al. 2022; Nair and Dasari 2022; Regazzi et al. 2019). Aside from it, several elements, such as the sort of material to be produced, part size, price, design specifications, and mechanical or physical properties, are all critical considerations.

Green composite production using sustainable fibers

Fibers from different sources with a variety of characteristics will be used in the production of polymer composites. The final requirements of the product typically determine the fiber selection. Mineral fibers are commonly used in products such as electrical insulators and boat hulls. Carbon fibers, which are most commonly manufactured from polyacrylonitrile fibers, are used in sports equipment, aerospace, and other applications (Tawiah et al. 2021; Rahnama and Rajabpour 2017). To employ such fibers as reinforcement, particular elements such as hemicelluloses, lignin, wax, and proteins must be eliminated to maximize fiber adherence. Wood pulp is also utilized to manufacture composite reinforcements since it is a type of laminated natural composite that is exceptionally robust (Hinestroza and Netravali 2014). Whenever a composite is produced from organic fibers, the matrix is responsible for maintaining the fibers in place, distributing tension, and transferring stress among the fibers. It also protects the fibers from mechanical breakdown and creates a buffer against the harsh environment (Bhattacharya and Misra 2004). Inside the composite structure, the matrices play a minor role in bearing the tension forces.

Nevertheless, the matrix chosen has a massive effect on the compression and shear properties of the material. The most commonly utilized lignocellulosic bast fibers for composite applications include ramie, jute, and flax. Bast fibers are made up of three main constituents: lignin, cellulose, and hemicelluloses. The main structural constituent of bast fibers is cellulose (Kabir et al. 2012). The major downside of the Cellulosic bast fiber is their hydrophilic character, which makes them incompatible with hydrophobic polymeric matrices (Debnath et al. 2013). An experimental investigation was conducted by António et al. (2018) on the acoustic, thermal, and mechanical characteristics of composite boards made of rice husk that were suggested for use in the building. Rice husk was mixed in 5–50 and 75–25 weight ratios with extended cork pellets or old rubber. A sufficient number of boards were made in order to conduct testing and assess qualities like sound absorption, sound impact insulation, thermal conductivity, compressive strength, and dynamic stiffness. The findings suggest that better building construction methods based on these composite materials might improve the thermal and acoustic properties of structures. According to Adeniyi et al. (2019), banana fiber-reinforced polyester composites have weak flexural strength and medium tensile strength compared to other natural fibers, including bamboo.

Production techniques of green composite

Green composites are made using a variety of production processes, including pultrusion, compression molding, injection molding, resin transfer molding, extrusion, and thermoforming Mann et al. 2020; Dong 2018; and Hu et al. 2012 used compression molding to make jute and polylactic acid composites, while Altun et al. (2013) used injection molding to make wood flour and polylactic acid composites. Furthermore, the TF process might be used to make polylactic acid composites as an alternative way (Faruk et al. 2012; Throne 2017). The manufacture of plastic composites for metal parts using direct long-fiber thermoplastics is a unique technology (Faruk et al. 2012). Manufacturing techniques are typically chosen based on the type and methodology of the material to be treated, the strength of the part, the intricacy of the component design, production capabilities, and investment requirements (Kopparthy and Netravali 2021). The manufacture of green composites using several processing methods such as compression molding and thermoforming, injection molding, prepreg sheet method, resin transfer molding, and vacuum bonding is discussed briefly in this article.

Compression molding

A novel study by Ambone et al. (2020) compared the mechanical performance of CNF/3D-polylactic acid composites made using 3D printing to those made using compression molding. The research used CNF produced from sisal fibers as reinforcement. Compression-molded composites were shown to have better tensile characteristics than composites that were 3D printed. Waxy maize or amylomaize native starch (waxy) was used as the green resin in a much more latest work by Regazzi et al. 2019, and softwood chemical-thermomechanical pulp and bleached and fibrillated chemical kraft pulp with lignin removed fibers were used as the reinforcements (Regazzi et al. 2019). The specimens were manufactured by molding stacks of numerous thin preforms created using a method analogous to papermaking utilizing either thermo-compression or ultrasonic compression. These composites showed an elastoplastic mechanical response, and their mechanical characteristics were on par with several commercial thermoset glass fiber reinforced composites and recently discovered green composites. In the study by Ramesh et al. (2020) aloe vera and kenaf fibers were sliced to a length of between 1 and 3 mm and first treated with NaOH. Extrusion and compression molding techniques were used to mix chopped fibers in a 30:70 ratio as reinforcement for polylactic acid (3052D, injection molding grade resin) (Ramesh et al. 2020). The impact strengths of the kenaf/polylactic acid and aloe vera/polylactic acid composites after treatment were 49.34 and 50.39 m^2, respectively, while the impact strength of the kenaf/aloe vera/polylactic acid hybrid composites after reinforcing hybridization was greatly enhanced to 69.29 kJ/m^2. Results indicated that kenaf and aloe vera fibers were extraordinarily compatible and sufficiently complemented one another to compensate for their weaknesses. In their deposition modeling and compression molding research, Roberto et al. (2022) concluded that excessive fertilizing may cause ecological problems because of percolating issues. An innovative green composite for exact release fertilizers was created by combining NPK fertilizer with a decomposable polymer through or without Opuntia Ficus Indica parts to address this issue and promote farming sustainability. Six preparations were synthesized and evaluated for the construction of devices for both compression molding and fused deposition modeling. Both fillers demonstrated excellent adherence to the polymer matrix, good dispersion within the composites, and effective reinforcement. It was feasible to adjust the NPK discharge rate by carefully selecting the particle size, adding Opuntia Ficus Indica, and synthesizing. The quickest release was seen in fused deposition modeling samples containing small amounts of NPK and Opuntia Ficus Indica. The mechanical characteristics of continuous-discontinuous sheet molding compounds by compression molding were examined by Trauth and Weidenmann (2018). Although continuous fiber-reinforced polymers give designers more opportunities to create intricately shaped components, mechanical performance is still subpar because of the finite fiber span and fiber alignment. Continuous-discontinuous sheet molding compounds seek to combine the advantages of unidirectional, continuous carbon fiber-reinforced composites and discontinuous, reinforced sliced glass fiber to overcome this issue. As natural green fiber is safer, healthier, and more environmentally friendly than petroleum-based materials, Hadi et al. (2018) concentrated their research on it. The impact of maleated anhydride polylactic acid on the mechanical characteristics of polylactic acid-reinforced pineapple leaf fiber was studied by the author. The various raw materials were combined in a hot rolling machine before being compression molded. Three tests were carried out: tensile, flexural, and water absorption. For processed polylactic acid nonwoven fabric composite and unprocessed polylactic acid nonwoven fabric composite, the findings of water absorption, tensile, and flexural testing were documented and discussed. It was found that composite materials made from natural hydrophilic fibers have less tensile and flexural strength. Ben and Kihara (2007a, b) studied kenaf and polylactic acid composite melt temperatures, holding times, and impregnation times. For kenaf and polylactic acid composites, a melt temperature of 185 °C and a holding period of 15 min was found to be ideal based on the mechanical properties of produced composites. For quasi-isotropic laminates, 30 s was indicated as the impregnation period. Nevertheless, the volume percent of fiber and polylactic acid was not given in the investigation, which is a crucial factor to consider while optimizing the manufacturing methodology. The effects of molding (both holding and impregnating) time and temperature upon wheat gluten-jute composite materials were also investigated by Reddy and Yang (2011). According to the results, the molding time and temperature of 170 °C and 15 min generated the best flexural characteristics. Curing temperatures for green composites should be between 150 and 180° Celsius, with pressure and time varying depending on the type of material employed and the thickness of the sheet or prepregs. In a study by Kim et al. (2019), the fiber alignment of the deformed woven fabric, produced by the vacuum-assisted resin transfer molding process, was considered for determining the permeability of a woven in-plane composite. A diagnostic model was put forth and connected to the results of the experiments to predict the permeability of the distorted woven fabric. Based on the existing model, the vacuum-assisted resin transfer molding process for the composite is based on the current model. The results of the vacuum-aided resin transfer molding experiment mirrored those of the model. It was claimed that the vacuum-assisted resin transfer molding simulation could accurately predict the outcomes of the vacuum-assisted resin transfer molding process, as well as the filling time and flow front pattern, taking into account the fiber directional permeability of the deformed woven fabric.

Thermoforming

Wang, B.J. and Young, W.B. (2022) investigated the mechanical properties of woven bamboo fiber-reinforced polypropylene composites. The bamboo fiber mat was made by hand, manually. The thermoforming technique was used to create the woven bamboo fiber/polypropylene composites. The tensile strength of the woven bamboo fiber/polypropylene composite with alkali-treated bamboo fibers was higher than that of the composite with unprocessed bamboo fibers. Once they are almost the same as in the transverse direction, the strength and modulus are nearly two times greater in the longitudinal direction. Based on overall thickness, composite sheets are roll-fed or pre-cut during thermoforming (Klein 2009). A clamping frame is frequently used to stop pre-cut sheets from twisting and warping. The sheets are then preheated to their glass transition temperature using convection or radiation heaters on one or both sides (Zampaloni et al. 2007). Preheating is advised before the forming operation to minimize the chances of material shear and premature fracturing caused by rapid cooling at room temperature (Lim et al. 2008; Zampaloni et al. 2007).

Further investigation of kenaf and polypropylene method variables found that the ideal forming temperature, die temperature, heating duration, and draw depth were 190 °C, 165 °C, 15 min, and 50.8 mm, respectively (Zampaloni et al. 2007). According to the researchers, such composite sheets have more excellent machinability because of fewer wrinkles and distortions. The process of thermoforming was used by Ville Leminen et al. (2020). Typically, this method creates plates or trays out of fiber-based materials like paper. These materials offer a biodegradable replacement for plastics in food and beverage packaging applications. The mechanical properties of the plates made from these composite materials are crucial to verifying that the parcels work as intended. The purpose of the study is to investigate the impact of heat input and the presence of the plastic layer on the robustness and compression strength of the molded trays based on dwell duration and heating temperature.

Open molding process

This procedure, often referred to as the open molding process for composites manufacturing, necessitates a high level of knowledge. Srinivasan et al. (2014) investigated the thermal and mechanical characteristics of a banana flax-based composite produced by hand layup and succeeded by compression molding. Using this procedure, one layer of banana fiber was sandwiched between the two layers of flax fiber. Dhawan et al. (2013) examined the effects of natural fillers on the characteristics of green fiber-reinforced polymers. Short fibers in the form of powder are employed in this technique. Lin et al. (2012) suggested an injection molding technique for the fabrication of wood-plastic composites. The study found that the weight of the wood-plastic composite was 5% less than that of the polypropylene/glass combination. The surface topography and dynamical characteristics of polylactic acid and polypropylene injection-molded composites with short sisal fiber reinforcements were investigated. According to scanning electron microscopy data, polylactic acid interacts more significantly with fibers than polypropylene. Mohanty et al. (2005) used an injection molding procedure to create soy-based bioplastic and chopped industrial hemp fiber to test their mechanical and thermal characteristics, which showed a remarkable enhancement. For the manufacture of sisal fiber reinforced with polylactic acid, Chaitanya and Singh (2017) contrasted the direct-injection molding process with the extrusion injection molding approach. The flexural and tensile strength of the biocomposites increased by 35% and 16%, respectively. Ohkita and Takagi (2011) used an injection molding procedure to create a bamboo/polybutylene succinate composite and measured its mechanical characteristics. A twin-screw extrusion was employed for the sample fabrication, and pellets of 40% weight percent were combined with PBS.

Utilizing mold opening technology, Xie et al. produced polylactide goods. Microcellular injection molding with mold opening technique was used to create microcellular polylactide and polylactide composites with void percentages as high as 50%. It was also noted how adding nanoclay to pure polylactide affected these characteristics. Different mold opening rates had the same effect on the cell structure and mechanical characteristics of polylactide-nano clay foams as they did on pure polylactide foams. The melt strength of polylactide-nanoclay foams was dramatically increased by the addition of 5 wt% nanoclay, which had a favorable effect on their ability to foam and their mechanical characteristics. It succeeded in increasing cell density and decreasing cell size (Xie et al. 2018).

Boards made of hybrid bio-composite materials were produced using a hot injection molding process. Hybrid bio-composite boards are sliced into pieces that may be tested for bending and compression using a “water jet machining technique.” The highest flexural strength, flexural modulus, and compressive strength for composites containing 35 wt% sugarcane fiber and 15 wt% Tamarind seed powder, respectively, were attained. For composites containing 40 wt% sugarcane fiber and 10 wt% tamarind seed powder, the minimum flexural strength, flexural modulus, and compressive strength were obtained. The hybrid bio-composites’ particular flexural and compressive performances are greatly enhanced by the constrained insertion of short sugarcane fiber and tamarind seed powder particles into the epoxy resin matrix (Girimurugan et al. 2022).

Agricultural wastes (cheap, renewable substrates) are employed as fillers in bioplastic composites because they are accessible and affordable. By varying the weight ratios of eggshell and walnut shell powders added to the plasticized polylactide, bioplastic composite samples are created. Five weight percent of epoxidized soybean oil is used to achieve the plasticization. Injection molding is used to further process the generated bioplastic granules into dog-bone-shaped samples that are then put through various mechanical, thermal, and optical microscopy testing. Automated tests for qualities like tensile, Charpy impact, and flexural gave lower results than virgin polylactide. When compared to plasticized polylactide-WS composite, the qualities of plasticized polylactide-ES composite performed better (Shaik et al. 2022).

In a recent study, how silane-treated pineapple leaf fiber with different fiber lengths—5, 10, 15, 20, and 25 mm—affect the characteristics of natural fiber composites was examined. It is of interest to achieve the best qualities for polyester composites using pineapple leaf fiber as a reinforcing material. The length of the fibers determines the properties of pineapple leaf fiber, and it is technically challenging to produce long fibers and process them for improved characteristics in polyester composites. To change the fiber characteristics, silane treatment is applied to the pineapple leaf fibers. Open-mold and hand lay-up methods were used to generate the polyester composites. The synthesized polymer matrix composites can be used to construct walls, building insulation, and artificial ceilings, thanks to their outstanding mechanical characteristics. (Anand et al. 2022).

Microcellular foamed wood-plastic composites have demonstrated promising development potential in composites that are environmentally benign. Here, the foamed WF/PP composites were made by mold-opening injection molding with supercritical N_2 acting as a physical foaming agent. Investigations were conducted to determine how nano TiO_2 would affect the microcellular structure and mechanical characteristics of WF/PP composites. The findings indicate that nano TiO_2 speeds up the crystallization process and reduces the crystallinity of PP, which is advantageous for the development of foamed homogeneous systems and cell growth in the WF/PP composites (Chai et al. 2022).

Molding with resin transfer

Continuous mats, woven rovings, and discontinuous lignocelluloses are made using the resin transfer molding technique. The main advantage of this technology is that the fiber orientation can be easily regulated (Liu et al. 2014). Wang et al. (2017) and Francucci et al. (2012) used RTM to create a unidirectional abaca fiber. With the assistance of a roller pump, the resin was injected into the mold through a silicon tube. They discovered that the RTM approach has a reduced manufacturing temperature requirement, which could also hopefully prevent mechanical degradation (Francucci et al. 2012). Another benefit of this method is the long-term durability of the high-strength components produced (Feldmann and Bledzki 2014).

Another recent study examined the environmentally friendly natural fiber composites made from nano-cellulose that were isolated from used paper egg trays and mixed with kenaf fiber using a vacuum-assisted resin transfer molding technique. To evenly combine the extracted nano-cellulose with the resin, three-roll milling, ultrasonication, and overhead stirring were used. The surface morphology showed a uniform distribution of extracted nano-cellulose in the composites, and a change in the transmittance percentage of the spectral peaks indicates that extracted nano-cellulose and the vinyl ester/kenaf composites had chemically interacted. (Yu et al. 2022).

In order to develop porous materials and increase compressibility, fast-growing wood (poplar wood) was delignified in this work using a steam mixture of hydrogen peroxide and acetic acid. The cellulose scaffold structure of the delignified wood was intact after processing, thanks to this method. The delignified wood and epoxy resin were then combined in a straightforward and environmentally friendly vacuum-assisted resin transfer molding procedure to create epoxy resin, named CDW/Ep, high-performance wood-based composites. Remarkable mechanical performance was demonstrated by the CDW/Ep specimens. (Liang et al. 2022).

Another study used resin transfer and compression resin transfer molding technologies to create high-performance wood strand panels for automotive applications. Resin transfer-molded wood strand composites demonstrated much higher mechanical characteristics and dimensional stability when exposed to moisture. (Gartner et al. 2022).

A recent study used vacuum-assisted resin transfer molding to create a continuous bamboo-textile-reinforced polymer composite utilizing woven bamboo strips and epoxy (vacuum-assisted resin transfer molding). Flexural characteristics of the samples, such as strength, modulus, integral load–deflection-deflection correlation, damage criteria, and fractography character traits, were also investigated. (Chang and Chang 2022).

Kottapalli et al. (2022) studied the impact attributes of hybridization and stacking sequence The laminates are made using the vacuum-assisted resin transfer molding process and have three alternative fabric orientations (0°, 30°, and 45°) for impact testing.

Seuffert et al. 2020, conducted research on models and experiments of pressure-controlled resin transfer molding. Simulation can accurately forecast the various stages of pressure-controlled resin transfer molding. The pressure and mold gap height decrease during filling, on the other hand, are extremely sensitive to tool geometry, process, and material parameters. Additional research is needed to examine the effect of characteristics such as permeability, viscosity, temperature, and tool geometry features such as sealing or fiber clamping systems.

RTM with vacuum assistance

For manufacturing flax fiber composite specimens, Kong et al. (2014) used a vacuum-assisted resin transfer molding, and the findings of different mechanical characteristics were compared to reference data. The results revealed that the mechanical qualities of a sample created using this procedure were superior to the findings of reference testing. Torres et al. (2003) investigated the single-screw extrusion for manufacturing organic fiber-reinforced thermoplastics and material characteristics characterization. Experimental investigations were also carried out to determine transport processes during single-screw extrusion to investigate the mechanisms of bubble generation caused by variations in fiber dispersion. Morphological characterization approaches were used to examine the framework correlations. Razali et al. (2021) worked on the use of resin transfer molding to develop structural components. This method of composite material fabrication employs an out-of-autoclave process. Out-of-autoclave offers significant advantages from the perspective of sustainable design, reducing the amount of energy used in production and reducing greenhouse gas emissions. Additionally, compared to an autoclave-based composite production method, out-of-autoclave offers economic benefits to yield parts at lower costs by allowing a shorter process life cycle and cheaper investment. Research using an out-of-autoclave process to create an airplane composite seat pan will provide a practical example of how the process works and contributes to the mechanical qualities of the product. Dai et al. (2018) concentrated on the vacuum-assisted resin molding technology for composite manufacturing. A series of biobased benzoxazine oligomers were constructed from furfurylamine, diamine, and paraformaldehyde derivatives of eugenol. Nuclear magnetic resonance spectroscopy and Fourier transform infrared spectroscopy are used to examine curing behaviors. Results showed that the oligomers had constant viscosities lower than 1 Pa•s during the temperature range of 60 to 190 °C and that their processing window was broader than 160 °C. The hardened resins displayed superior thermal, hydrophobic, and moisture-resistance performance.

Rashid et al. (2021) assessed the impact of applying through the thickness reinforcement by tufting in a flax-based composite laminate on in-plane mechanical characteristics. As anticipated, the glass fiber tufts enhance the link between the core and skin of the composite, increasing the interlaminar shear strength calculated from flexural testing with a short span-to-thickness ratio. An increase in interlaminar shear modulus is highlighted by digital image correlation done during shear tests.

Midani and Hassanin (2021) employed vacuum aided resin transfer molding technology to produce an Electromagnetic interference shielding composite material by mixing carbon fiber sheets and wood veneers with epoxy resin infusion. The flexural and tensile strengths of the composite were six and three times that of natural poplar, respectively. The composites outperformed poplar in terms of thermal conductivity, water resistance, and surface hydrophobicity. The inclusion of carbon fiber sheets increased not just the mechanical performance of samples, but also their potential to shield electromagnetic signals. This article discusses a revolutionary technique for creating a natural bio-based high-strength composite material for electromagnetic interference shielding purposes.

Negawo et al. (2021) wanted to know how stacking sequences affected the mechanical and dynamic mechanical properties of ensete/glass hybrid composites. The composites were created utilising a vacuum-assisted resin transfer molding process and four layers of carded ensete web and woven glass fabric. Hybrid composites' mechanical and dynamic mechanical characteristics were studied. The results of the tests revealed that combining ensete web with glass woven fabrics improved the mechanical properties of ensete composites.

Shunmugasundaram et al. (2021) investigated the influence of nano-filler on the tensile characteristics of natural-based polymer composites. The majority of research for the development of novel composites use only one nano-material. In this study, the vacuum aided by infusion molding process was used to develop new nano infused composites by combining neem fiber with two different nano-filler materials. The average ultimate tensile strength for the polymer matrix composite is 15.5% after infusing nanofiller materials into nano-based natural fiber polymer composites.

Bai et al. (2021) prepared bamboo fiber-reinforced epoxy resin composites using vacuum-assisted resin transfer molding, and the tensile characteristics were determined. The outcomes demonstrated that adding a wetting agent might significantly increase the interface compatibility of bamboo fiber-reinforced epoxy resin composites. The interfacial shear stress of bamboo fiber-reinforced epoxy resin composites treated with 1% wetting agent was 24.36 MPa, the tensile strength and Young's modulus were 165.7% and 66.7% higher than for untreated bamboo fiber reinforced epoxy resin composites, respectively.

Pultrusion

By impregnating the fiber with a thermosetting matrix and pulling it through a heated die, pultrusion is a fabrication procedure for composite profiles. Generally, this fabrication method can be run continually to generate symmetric sectional profiles with significant volume rates. The pulling, heat transfer, and pressure zones are the three primary zones that make up the pultrusion process (Asyraf et al. 2020). The fiber tapes are drawn via a thermosetting polymer resin solution, and the output determines the finished shape of the die cross-sectional area. The pultrusion method can be used to make composites with reinforcing materials made of natural fibers like kenaf, jute, and hemp or synthetic fibers like glass and carbon fibers (Fairuz et al. 2015). Determined by the geometry of the die, the goods are generally in the shape of a bar or the shape of rods. The finished products are trimmed to the desired length, and composite curing is also necessary for the die. The main benefit of this technique is that it may produce components with consistent cross-sectional design while running continually (Lehtiniemi et al. 2011). Furthermore, this procedure is highly economical (Curtis et al. 2000).

Filament winding

A robotic fabrication process called coreless filament winding modifies traditional filament winding to use the least amount of core material possible. Through a number of pavilions, this technique was introduced and improved, showcasing its potential to build lightweight structures. The most recent project, Maison Fibre, takes things a step further and transforms the fabrication into a hybrid structure that combines laminated veneer lumber and fiber-polymer composites to enable walkability. The end result is the first system for multi-story buildings made using this unique fabrication method. Using fiber-polymer composite materials, coreless filament winding is a cutting-edge fabrication technology that effectively creates filament-wound structures for architecture while minimizing production waste (Pérez et al. 2022a, b). This article evaluates various fibers, resin systems, and the required coreless filament winding fabrication changes in order to design and build a bio-composite structure, the LivMatS Pavilion. The methods incorporate small and large-scale structural testing along with material evaluation and characterization at various phases of the structural design loop. The outcomes show the interactive decision-making method that utilizes feedback from structural simulations and material characterization to evaluate and optimize the structural design. Continuous fibers infused with resins are coiled around a spinning mandrel with the correct shape, and the resulting resin is cured and processed to produce a material with the right consistency (Ratwani 2010). In this procedure, fiber strands are continually unwound and run through a resin tank. Such strands are then transferred onto a revolving mandrel and looped around it in a coordinated manner with a specified fiber configuration (Lehtiniemi et al. 2011). Ansari et al. (2017) investigated the mechanical characteristics of organic fiber yarn-reinforced composite structures. Flax and kenaf fiber tube samples were made utilizing a filament winding procedure, and the characteristics of the specimen were evaluated against E-glass fiber composites. The findings demonstrate that E-glass fiber composites had better qualities than flax fiber composites in some areas, although flax fiber composites' tensile strengths were comparable to E-glass fiber composites. Fairuz et al. (2014) investigated the influence of winding angle on different mechanical characteristics of filament exposed to uniaxial and biaxial stresses.

Environmental friendly green composites

Composites, as versatile materials having outstanding qualities, have a wide spectrum of uses in industries such as automobiles, aviation, and shipping (Adekomaya 2020). Concerns regarding the environmental effects of composites with two or more ingredients have grown in the last decade or so. Green composites have indeed been designed to establish composites that are environmentally beneficial. Most are either entirely biodegradable or moderately biodegradable. Due to their biodegradability and sustainability qualities, composites derived from natural and/or renewable resources are envisioned as the future materials to satisfy the expanding demand globally. Due to its multifunctional qualities and widespread applicability in industries like automotive, maritime, aerospace, structural and infrastructural applications, packaging, the electronics industry, sports, and biomedicine, green composites are the subject of much research. They also exhibit replacement potential for costly, non-biodegradable, petroleum-based composites. It may be readily disposed of after its shelf life without affecting the environment. (Islam et al. 2022a, b). Biocomposites, an exciting new material with several uses and a replacement for conventional composite materials, are made of a polymeric matrix and reinforcing fibers. Biocomposites must adhere to the green chemistry principles, which are a component of the sustainability idea, in order to be categorized as biodegradable and green (Rafiee et al. 2021).

Natural fibers

The wood material is a multi-layered organic composite, rendering it incredibly robust; the wood pulp is also utilized in the manufacture of composite reinforcement (Hinestroza and Netravali 2014). Organic fibers have poor mechanical characteristics compared to synthetic materials such as Kevlar and aramid. However, this weakness can be overcome by enhancing the density of the organic fibers (Mohanty et al. 2004). Organic fibers do have advantages over synthetic fibers, including recyclability, good biocompatibility, environmental friendliness, superior insulating characteristics, and reduced machinery wear (Chichane et al. 2022). Due to their eco-friendliness, lightweight, exceptional life cycle, good biocompatibility, low price, and exemplary mechanical properties, natural fiber-reinforced polymer composite materials are becoming more and more popular these days. Industrial applications for natural fiber-reinforced polymer composites are numerous, and research in this area is constantly growing (Shaharul Islam et al. 2022a, b). Natural fibers may be able to replace synthetic fibers in the future, provided their moisture-absorbing characteristics are lowered, and fiber lengths are extended to improve mechanical characteristics. Plant fibers are derived from many parts of a plant, such as leaves, fruits, stems, straws, and grasses (Kumar et al. 2021a; Satyanarayana et al. 2009; La Mantia and Morreale 2011), and are studied in detail by numerous researchers. Natural fibers, on the other hand, have several drawbacks as compared to synthetic fibers, such as product variance owing to factors such as plant age, climatic and geographical growth circumstances, cultivation techniques, and cleansing technology. Likewise, there is indeed a considerable variation in mechanical characteristics between natural and synthetic fibers, owing to natural fibers' shorter length. Organic fibers' moisture absorption properties lower their adherence, making composite production time-consuming. The hydrophilicity of such organic fibers causes clumping during manufacturing. Bast fibers are often used in the production of green composites, but other species are now being explored for research into green composites. Perennial grass is a single-seed species that requires less fertilizer and water, making it an ideal choice for composites. The prospect of switchgrass as a reinforcement material for composites was investigated, and it was discovered that switchgrass polypropylene composites had superior mechanical qualities over jute fiber composites. Polypropylene composites can be extremely beneficial in generating green composites with improved quality (Zou et al. 2010).

Animal fibers

Conventional animal fibers such as silk and wool have been investigated as reinforcing materials for green composites. Due to their flexibility, high aspect ratio, toughness, and lower hydrophilicity than other organic fibers, animal fibers have piqued attention as high-performance fibers (Kumar et al. 2021a; Surip et al. 2016); Dinesh et al. (2020) investigated three specimens made using different combinations of the natural fibers goat wool, hen feather, human hair, and Kevlar 29 (K-29) that are reinforced with epoxy resin using the hand layup process. The compression molding technique was used to apply homogeneous pressure to sandwiched layers. According to ASTM standards, tensile and flexural strength tests are conducted. In addition to this, a water immersion test is also performed to figure out how much water is absorbed under particular circumstances, scanning electron microscopy analysis of bonding layers, and structure. Their study demonstrated that composite materials have improved mechanical characteristics and very little water absorption. It is employed for its small size and wide range of applications in the engineering sector as well as for maritime environmental lining materials. Keratin fibers, for example, contain a substantial amount of air, resulting in low-density fibers with a low dielectric constant, making them excellent for use as reinforcement material in electronic applications. Plant fibers have a short fiber length, which contributes to their poor tensile strength. However, some animal fibers, such as silk, have a continuous fiber length (1500 m), which provides them with better mechanical characteristics.

Due to its unique characteristics, spider silk is more rigid than steel and Kevlar. The amount of material used in a variety of engineering disciplines, such as mechanical and civil, might be significantly reduced by this material. In this study, a structural model of an airplane windowpane is analyzed, and the results are contrasted with the current industry standard material. Spider silk is a perfect fabric for composites due to its outstanding elastic characteristics. Spider silk fibers are used in the composite material as reinforcement, and epoxy serves as the matrix (Mayank et al. 2022). The mechanical performance of silk is also influenced by the type of silk used and the technique of spinning. Silk has limited temperature resistance, yet it is extremely antimicrobial and ultra violet-resistant. Silk composites are used in biomedical applications such as creating grafts and tissue engineering. Animal fibers do not require fertile soil or freshwater to grow, making them a more sustainable option. However, animal fibers can be expensive and have an unclear supply, which is a disadvantage (Farhad Ali et al. 2021). Fibers from wastes are a much more sustainable option for reinforcing material since they are part of an agro-industrial waste that is used to make a novel material; this not only offers an inexpensive raw material but also serves as a final disposal option for agricultural residues (Xiao et al. 2020a, b). For example, maize husk, for example, is easily accessible from corn manufacturing firms, which solves the issue of organic fiber source and geographic factors. The mechanical characteristics of rice husk and lignocellulosic biomass waste strengthened on polyethylene matrix have been investigated. Sunflower stalks, rice husks, corn husks, wheat straws, soy, and sunflower stalks are examples of agro-industrial wastes that can be employed as cellulosic fiber sources for reinforcements (Zini and Scandola 2011). Animal processing firms, such as those that process ham, duck, and chicken fillets, generate large amounts of protein wastage comprising feathers, wool, and other materials that can be used as reinforcing materials in composites (Bansal et al. 2021). Chicken feather fibers are extensively available throughout the world, as chicken is one of the most widely consumed foods (Rittin Abraham Kurien et al. 2022). Because of their porous structure, these fibers have a low density, making them suitable for usage in automobiles. Keratin fibers reinforced on PP were examined, and the polymer composite demonstrated enhanced stiffness with reduced temperature resistance up to 200 °C (Barone et al. 2005). Waste used to generate cellulosic and keratin-based fibers necessitates preliminary waste processing but also aids in waste disposal while also offering durable and efficient reinforcement for green composites. Agro-polymers, such as cellulose, microbial polymers generated through microbial fermentation, such as polyhydroxy alkanoates, chemically synthesized by agriculture and agri resource monomers, and chemically synthesized by traditionally manufactured monomers are all examples of biodegradable polymers. Processing biopolymers into composites entails a number of critical steps. Biopolymer treatment in composites includes a number of critical elements, including the breakdown time and temperature of the polymer, as well as its density, which determines the density of the finished composite material (Baillie and Jayasinghe 2017). The rigidity and tensile strength of natural polymers can be improved by strengthening with lignocellulosic fibers with considerable tensile strength.

Characterization methods of green composites

This section discusses the various characterization methods of green composites, such as compression molding, thermoforming method, open molding process, molding with resin transfer, resin transfer molding with vacuum assistance, pultrusion, and filament winding. In the compression molding method, fibers are inserted into a metallic mold, and resin is poured directly into them. After that, the material is pressed at 150 °C and cooled to room temperature. Thermoforming method composites are produced by hot pressing the preforms of resin-pasted fibers. Firstly, the fibers are wound and stretched around a metallic plate, and then resin is applied to the fibers using a small brush. Finally, fibers embedded in the resin are dried at 30 °C for 24 h. Afterward, dried preforms are pressed by 6.54 MPa at 150 °C for 1 h. The heating process is stopped, and a pressure of 13.1 MPa is applied to it until the material reaches room temperature. Fibers are placed in the metallic mold, and resin is applied to them. Then the fiber sheets are obtained by pressing those resin-pasted fibers slightly at 120 °C. Afterward, a set of five sheets, each with identical fiber orientation, is inserted in the mold and pressed by 3.27 MPa at 150 °C for 1 h, and a pressure of 16.9 MPa is applied to the set until the temperature approaches room temperature. Liu et al. (2019) carried out the characterization and modification of maize stem fibers that have been isolated from corn stalk waste. The chemical characteristics, surface morphology, mechanical behaviors, and thermal stability of the corn stem fibers were studied after the alkali, silane, and NaOH-silane solutions were applied to the corn stem fibers. The maize stem fibers' chemical and mechanical qualities were enhanced by the surface treatments. After the surface treatments, the fibers' surfaces were rougher. The surface treatments eliminated some hemicelluloses, lignin, and pectin from the natural fiber surface, according to energy dispersive X-ray analysis and simple infrared spectrophotometer analyses. The findings of the X-ray powder diffraction examination demonstrated that the surface treatments had a favorable effect on the natural fibers' crystallinity index, the modified maize stem fibers' mechanical qualities, and thermal stability. In a recent study by Kumar et al. (2017), a mixture of polypropylene and maleic anhydride-grafted polypropylene as the base matrix and a weight ratio of 9:1 is maintained for the entire experimental work. Loading of treated hollow glass microspheres is maintained constant at 10 wt% with respect to the base matrix. The loading of simulated body fluid is increased from 0 to 20 wt% with respect to base matrix. The structural and mechanical properties, namely density, tensile strength, tensile modulus, flexural strength, flexural modulus, and impact strength, have been evaluated. Morphological observations to confirm proper filler dispersion and wetting have been captured with scanning electron microscopy. The morphological analyses performed using scanning electron microscopy demonstrated satisfactory wetting of both fillers. The research opens the door to the engineering and design of components based on other prospective light-weight, high-strength natural fiber-based composites. Various mechanical characterization techniques can be used to effectively determine the mechanical behavior of composites. The effect of natural fibers as reinforcement is studied through various characterization techniques (Nithesh Naik et al. 2022; Zarges et al. 2017). The mechanical properties of green composites depend upon multiple parameters such as fiber aspect ratio, percentage of fiber content, surface treatment of fibers, and coupling agents to increase the bonding between fiber and matrix (Sullins et al. 2017; Amir et al. 2017). Various tests determined the mechanical characterization of fibers, such as tensile strength, Young's modulus, compressive strength, flexural strength, flexural modulus, and impact strength, including the Charpy/Izod test and shear strength. Ciupan et al. (2017) studied the mechanical properties of hemp fibers and polypropylene-based natural fiber composites. He observed that the tensile strength of the composite had improved due to the addition of natural fibers for both composites. Tensile strength and Young's modulus of hemp fiber-based composites were higher than polypropylene-based composites but it also showed a decrease in impact strength as compared to the hemp fiber-based composite because of the stress concentration region around the natural fiber bundle. Fiber treatment improved the interfacial interaction, thus resulting in improved properties (Ranjan et al. 2013). As the fiber content in the loading direction increases, the Young's modulus and tensile strength of both poly lactic acid-self-reinforced composites and poly lactic acid-butylene succinate composites increase. Liu et al. observed that the prepared natural cellulose fiber composite had a 42% higher impact strength than the corn stalk composite. Silane-treated fibers and 3% C30B nano clay offered better strength and modulus due to the formation of hydrogen bonds of nano clay between fiber matrix interfaces (Sajna et al. 2014). Srinivasan et al. (2014) observed that the tensile strength of the flax-banana based glass fiber reinforced plastic composite is 39 N/mm^2, which is higher than the banana-based glass fiber-reinforced plastic composite with 32 N/mm^2 and the flax-based glass fiber reinforced plastic composite with a value of 30 N/mm^2. Flax-banana-based glass fiber-reinforced plastic composite has an excellent ability to absorb impact forces compared to banana-based glass fiber-reinforced plastic composite. In another study by Kamaruddin et al. (2022), thermoplastic cassava starch–palm wax blends reinforced with the treated Cymbopogon citratus fiber (TPCS/PW/CCF) were successfully developed. The thermoplastic cassava starch was previously modified with palm wax to enhance the properties of the matrix. The influence of alkali treatments on the thermoplastic cassava starch–palm wax blends reinforced with the treated Cymbopogon citratus fiber biocomposite was analyzed. The fiber was treated with different sodium hydroxide (NaOH) concentrations (3%, 6%, and 9%) prior to the composite preparation via hot pressing. The obtained results revealed improved mechanical characteristics in the treated composites. The composites that underwent consecutive alkali treatments at 6% NaOH prior to the composite preparation had higher mechanical strengths compared to the untreated fibers. Surface treatment results in improved tensile and flexural properties and decreased impact strength (Goriparthi et al. 2012). Composites containing 20, 40, and 50% date palm fibers have lower void fractions, while composites with 60 and 80% have higher void fractions (Ibrahim et al. 2014). The flexural properties increased with 30 to 50% flax addition, and with an increase in silane addition, the tensile and flexural properties increased (Fu et al. 2014). Both Young's modulus and tensile strength were large for the kenaf/polylactic acid composite as compared to polylactic acid alone (Ben et al. 2007). Ibrahim et al. (2014) suggest that green composites with higher modulus will be a strong candidate for replacing glass fiber composites. The flexural strength of polylactic acid was greatly improved by introducing chopped jute and kenaf fibers to the polylactic acid matrix. Surface-modified fibers showed better tensile properties than untreated fibers due to the presence of a higher percentage of crystalline cellulose. A detailed literature study on the characteristics of green composites is performed, and different processes are classified. Research can also be required to reduce the cost of biopolymers as a matrix material.

Significant applications of green composite made from sustainable raw materials

Organic cellulosic fibers are primarily utilized to reinforce non-biodegradable plastics in order to develop green and sustainable composites (Abdelhamid and Mathew 2022). Their popularity has grown as a result of their low cost and global ease of access (Hasanin 2022).

Because of their hollow as well as cellular nature, such fibers are non-abrasive to production equipment and operate quite well with thermal and acoustic insulation materials. Furthermore, treatment options like mercerization and silanes were shown to improve mechanical characteristics while decreasing moisture responsiveness. Thermosetting resins like epoxy and polyurethane were also utilized with plant-based fibers (Awais et al. 2021; Petrenko et al. 2022). Nevertheless, the majority of such composites are produced from sawdust, a waste product of sawmills, or wood fiber acquired by processing wood. Such composites, known as “wood–polymer composites,” are extensively utilized in non-structural applications containing wood fiber (Wiener et al. 2003).

Natural-fiber composites have been used in automobile parts by a number of automakers, including Audi, BMW, Fiat, SEAT, and Volkswagen. These businesses have used these composites in things like door panels, luggage racks, seat cushions, backrests, and cabin linings. For medical devices used to repair and regenerate tissue damage, there has been a movement in recent decades from the use of biostable biocompatible materials to bioabsorbable or biodegradable biomaterials (Vázquez-Núñez et al. 2021).

Given their versatility in chemistry, which results in materials with a large range of physical and mechanical properties, biopolymers have demonstrated tremendous opportunities. Biopolymers have been successfully used in numerous biomedical and other technical applications from its inception, including controlled medication delivery, food packaging, the construction industry, regenerative medicine, wearable electronics, orthopedic, and long-term implants (Arif et al. 2022).

Azmi et al. (2019) developed a bulletproof vest employing X-ray films and woven kenaf by layering several composite configurations and using epoxy resin as a matrix. In this study, hand lay-up epoxy-based hybrid composites were made, and their flexural and high velocity impact resistance were assessed.

Biopolymers have been observed to be biocompatible and biodegradable, making them suitable in a wide range of applications, including edible films, emulsions, packing material in the food industry, drug carrier materials, medical augmentations like organ, tissue scaffolds, wound repair, and dressing materials in the pharma industry (Udayakumar et al. 2021). The industries have been able to tackle these issues, thanks to sustainable and biodegradable food packaging materials based on biopolymers. Due to their superior biodegradability, renewability, bioavailability, and non-toxicity, these efficient and environmentally friendly materials are also reducing the ecological concerns with regard to plastic-related pollution. Green technology application is projected to improve food quality and safety by lowering food wastage and plastic wastage, which will actually facilitate environmental sustainability objectives (Khalid and Arif 2022).

Natural fiber-reinforced polymer composites have attracted enormous interest from a wide range of automotive firms, including the proton organization (Malaysia’s national automaker), Cambridge industry, and German auto organizations (BMW, Audi Group, Ford, Opel, Volkswagen, Daimler Chrysler, and Mercedes) (a car industry in the USA) (Khalid et al. 2021).

NEC Corporation introduced a newly manufactured plastic in June 2005 that combined biomass-based additions such as kenaf fiber and polylactic acid. This innovative kenaf fiber-reinforced polylactic acid composite material had the largest proportion of renewable resources of any biocomposites used in electronic equipment (Zhou et al. 2022).

In September 2004, it was launched in collaboration with Unitika Ltd., when the material was utilized to create a fake card for a desktop pc. In contrast to petroleum-based polymers employed in dwellings, like glass fiber-reinforced acrylonitrile butadiene styrene resin (50), these composites demonstrate strong practical qualities for household components of electronic goods. Youssef et al. (2015) examined the fortification of biopolymer films employing nanoparticles as well as additional treatments, concluding that nanocomposites can minimize combustibility while maintaining the transparent nature of the polymer to a certain extent (Tirado-Kulieva et al. 2022).

Because of their improved mechanical and thermal properties, such composites are also a suitable alternative for packaging, and the dispersion of nanoparticles allows them to be used to store fruits, veggies, and liquids. In contrast to oil-based polymer packaging options, Davis and Song (2006) investigated the implications of biodegradable packaging on the management of waste. Highway and airport runway concrete pavements, bridge components, housing, and industrial flooring, as well as other related applications too, can benefit from concrete composites incorporating-waste carpet fibers. Utility concrete components such as subterranean vaults, including junction boxes, industrial waste pipes, sewerage channels and pipelines, and power cable transmission towers could all benefit from this kind of concrete composite (Awal and Mohammadhosseini 2016). Hybrid composite structures have indeed been formed using widely different proportions of glass and carbon-knitted fabric in epoxy matrices, and it is been demonstrated that, when used on the outside, composite laminates with a 50% carbon fiber reinforcement proportion demonstrate the strongest flexural characteristics, while an alternating carbon/glass lay-up configuration guarantees the best compressive behavior (Zhang et al. 2012). Natural fiber composites are crucial in the quest for alternative materials in the auto industry since they integrate special attributes, such as noise and vibration abatement capacity and decreased weight (Suddell and Evans 2005).

It is reported that nearly 75% of the total energy usage of a vehicle is explicitly linked to variables correlated with the weight of the vehicle (Mohanty et al. 2002; Salonitis et al. 2009). Nanofibrils offer a wide range of potential applications in fields such as medicine, cosmetics, energy, electronics, the environment, and textiles (Trache et al. 2022).

In the medical field, they can be used as medication carriers, prostheses, bandages, surgical materials, and so on. The high specific surface area and absorption coefficient of cellulose fibrils make them an attractive option for usage in creams, masks, and other cosmetics. Cellulose fibrils can also be found in electrical devices such as computers and radiation guards. Cellulose fibrils are used in textiles, apparel, and other products (Yang et al. 2022a, b).

Polylactic acid and starch are employed to make lawn grass, coffee cups, pencils, and blades. Cellulose fibrils can also be used to make nanofilters, sensors, adsorbers, and filters, among other things (Ahmad et al. 2022).

Some of the above application areas are still in the research phase, but there are few materials manufactured from nano-fibrillated cellulose that are available on the market; thus, cellulose could be a viable alternative to petroleum-based polymers if only high-productivity and low-cost cellulose nanofibril manufacturing processes are established (Janaswamy et al. 2022).

The use of natural fibers for building industry will aid in the development of more sustainable construction materials (Yan et al. 2014). As previously stated, wood-plastic composites seem to be the most popular in the construction industry, as previously stated. Interior panels, decks, rails, window framing, exterior furnishings, tables and chairs, gardening seats, pallets, planks, bridges, and other items are the most typical applications (Shah et al. 2013; Bharath and Basavarajappa 2016). Interior and exterior floors, restroom floor tiles, vessel soleplates, subway and vehicle floors, interior and exterior furnishings, lawn furniture, doors and windows, and facade materials are just a few of the application areas for bamboo fiber-reinforced composite materials. Biocomposite applications have a lot of potential in the sports and recreation industries (Ilangovan et al. 2022).

Plant fiber-reinforced composites have been employed in sports and leisure outdoor applications with great success (Rangappa et al. 2022).

They are used in boat hulls and canoes, skateboards, surfboards, bicycle frames, sports rackets, dolls, musical equipment, and more because of their outstanding vibration damping, safety and health properties (Shah et al. 2013; Bharath and Basavarajappa 2016). Rosa et al. (2014) investigated the environmental implications and thermal conductivity study of several building wall materials in order to fully comprehend the influence of environmental modifications on the green composites' product lifecycle. The material was manufactured and tested for thermal conductivity using natural fibers like flax and bio-based epoxy. The results revealed that employing eco-sandwiched materials reduced environmental consequences (Özdemir and Önder 2020). Recyclable materials, indigenous resources, construction, and material reclamation, are all included in green composites' architectural and structural applications (Yudelson 2010). Green composite bars have been used in construction to substitute conventional steel bars, resulting in structures that are significantly earthquake resistant (Al Faruque et al. 2022).

Concerns about the production of green composites

The fundamental issue in producing green composites is that they must survive extreme heat while removing the odor produced by natural fibers such as kenaf, hemp, and jute (Sinha and Devnani 2022). Natural fiber-based composites are quite expensive, which is not acceptable to the massive automotive sector (Islam et al. 2022a, b). Insufficient knowledge about the functioning of sustainable and green composites, owing to an enormous diversity of ingredients, is the greatest difficult hurdle to surmount in this industry (Vinod et al. 2020).

In order to achieve good-quality composites, the first essential task is to choose the correct manufacturing circumstances and factors, as well as a precise choice of composite ingredients and overall material qualities. Natural fibers' poor qualities are a fundamental issue that restricts their use in green composites (Shekar and Ramachandra 2018). Additional issues that several green composites face include the requirement that the material source has little effect on the entire lifecycle impact on the environment (Kupolati et al. 2022).

The major characteristics of sustainable development are energy consumption, longevity, and the quality of services (AL-Oqla and Omari 2017).

The recycling of discarded composite materials towards the expiration of their functional life should be considered throughout the design phase of the product (Lu et al. 2022). Plastic trash has indeed been identified as a significant environmental issue. Consumers have expressed worry about the discharge of contaminants and chemicals in plastic consumer goods (Chen and Selvinsimpson 2022).

Plastics are somewhat inevitable materials in many aspects of modern civilization, including medical services, distribution of food, construction materials, automobiles and mobility, and wrapping for household devices (Li et al. 2021a, b). Material reclamation that is both ecologically sound and technologically effective should be implemented, particularly in countries that are overpopulated (Elsheikh et al. 2022).

The latest scientific visions in the green sustainability domain

The necessities of human civilization, which include fuel, power, and freshwater, have engulfed technological exuberance and complexity in recent years. Scientific and technological prowess nowadays is rich with foresight and perseverance (Dutta et al. 2022). Modern civilization requires industrial sewage treatment, potable water treatment, and water purification (Kuhn et al. 2022). In the sphere of environmental sustainability, scientific perception is in trouble, as is comprehensive awareness. In the development of nanoscience, the challenges of research are currently establishing new possibilities for scientific independence (Pasupuleti 2022).

Presently, technology and science are at a crossroads in terms of ecological, energy, as well as environmental sustainability. In an advanced and emerging world, environmental sustainability is a true cornerstone of human scientific endeavors (Thakur and Thakur 2022). Managing freshwater scarcity is a pivotal challenge requiring scientific and educational integrity in modern times. This paper adequately tackles the major goal of environmental and energy conservation deployment. As a result of human activities ranging from the utter devastation of forested areas to the hydrocarbon emissions in our cars and industrial air pollution, the environment has changed tremendously (Raihan and Tuspekova 2022; Dhakal et al. 2022).

The troublesome water-related problems of arsenic as well as heavy metal groundwater pollution ought to be re-evaluated with the passing of scientific thought, forbearance, and the idealistic time scale of human existence (Sharma et al. 2022). Sustainability motives, according to another report, are frequently complicated, subjective, and diversified (Khan et al. 2022).

With the passing of scientific thought and conceptual time frames, the broad perspective of the realm of environmental and economic benefits must be reformed and rebuilt (University of Alberta Office of Sustainability Report, 2010). The key characteristic of this research is that it underlines the critical role of modern human civilization in achieving genuine social, financial, ecological, and sustainable development (University of Alberta Office of Sustainability Report, 2010). The concept of sustainability has evolved significantly throughout time (Erlygina and Shtebner 2022).

The term sustainable development would not dwindle away in this frenetic era of growing limited resource scarcity, global warming, and continued worldwide rising population, paired with worldwide modern economic and social development (Yanarella et al. 2009; Talan et al. 2020).

Green restoration and applying ecologically sustainable methods to the restoration of polluted sites were clearly understood in a US Environmental Protection Agency report (the United States Environmental Protection Agency Report 2008). Currently, environmental engineering and protection are on the verge of a new technical and scientific renaissance. A recent article by Yang et al. 2022a, b envisioned long-term viability of the site remediation, as well as site management practices, power and efficiencies, instruments and rewards, and future potential (the United States Environmental Protection Agency Report 2008). The US Environmental Protection Agency is committed to continuing to develop and facilitate inventive bioremediation methodologies that reinstate polluted land to beneficial usages, decrease additional expenses, and encourage environmental and energy governance as part of its global quest to safeguard the environment and public health (Young et al. 2022; Arslan et al. 2022). Hazardous or critical pollutants such as fine particulates and lead produce air pollution (Jain et al. 2022). Unbalance in the water cycle (the United States Environmental Protection Agency Report 2008), soil erosion and nutrient loss are both problems (Dou et al. 2022). With declining populations and rich biodiversity, nitrous oxide, methane, carbon dioxide, and other greenhouse pollutants are released (Sonwani and Saxena 2022). Preserving water and water purity are two important goals; enhancing the effectiveness of energy and water, toxics management and reduction, and cutting the number of certain air contaminants released into the atmosphere, are the distinguishing traits of the US Environmental Protection Agency's concept of scientific order to pursue (Shapiro 2022).

Nanotechnology and environmental consequences of its products

Nanomaterials based on organic compounds

Several typical organic polymers can be manufactured in nanometric scales (Andre et al. 2018). Under specific circumstances, the resulting polyvinyl chloride or latex could, for instance, be solubilized or chemically changed. Several of these natural polymers could be made into nanowires, allowing them to be used in the creation of liquid and gas-phase ultra-filtration systems, as well as sensors (Broza et al. 2018). Certain readily biodegradable nanofibers could be employed in medicine to help with tissue regeneration and drug release management (Tomalia 2004; Priya et al. 2022). Biologically influenced nanomaterials come in a wide range of shapes and sizes, but they typically encompass structures that embody, bait, or absorb biological materials on their surface (Thomas et al. 2022).

Fatty acids, peptides, and polysaccharide-based nanoparticles, in particular, are employed as vehicles for targeted medication delivery (Upadhyay et al. 2022). For instance, micelles, liposomes, and polyplexes, for instance, have been discovered (Kumar et al. 2021b). Many of them have been extracted from renewable materials, and others have been synthesized. Inside the medical and pharmaceutical disciplines, such nanostructures have been extensively investigated (Yadav et al. 2022). In a nutshell, nanoscience and customized nanomaterials bring novel material conceptions and properties that can be used in a broad variety of materials and applications (Munir 2022). Mankind has adjusted to the existence of organic nanomaterials in their environments, though perhaps not completely (Saleh (2022).

Environmental consequences of employing nanoparticles

The fundamental worrying sign concerning the environmental problems offered by engineered nanoparticles is the question whether such unique features produce interactive impacts across an ecosystem in a manner that is distinct from those of conventional substances (Kumar et al. 2022). From the perspective of the ecosystem, the concern will be if the changes in chemical composition and a greater variety of subtypes of nanoparticles caused by their entry into the environment amplify the impact on the ecosystem in question (Salem et al. 2022b).

Nanoparticles have a greater surface area than conventional materials. Hence, they can threaten the human body and the surroundings more so than larger materials (Fiordaliso et al. 2022). As a result, domestic and global emphasis has been drawn on the possible harm that nanoparticles pose to society (Warheit et al. 2004; Borisova (2022). There seem to be two primary mechanisms for releasing nanoparticles into the environment (Zahra et al. 2022). Nanoparticles are released into the air from a source categorized as a primary emission, and they account for the majority of overall emissions (Marcano et al. 2010; Saleem et al. 2022a). Contaminants can conveniently be bonded to nanoparticles and moved towards a more vulnerable environment, like aquatic environments (López et al. 2022). Radioactive material waste, for instance, migrated over a mile beyond a nuclear facility in 30 years (Nematchoua and Orosa 2022).

Nevertheless, after four decades after this incident, the very first flow mechanism model to explain the ways of nanoparticle waste transportation was established (Salas et al. 2010; Brewer et al. 2022). The following is a summary of the potential environmental impact caused by nanotechnology: synthesizing nanoparticles necessitates a large amount of energy, resulting in high energy consumption (Fajardo et al. 2022).

Dispersion of hazardous, long-lasting nanomaterials causes environmental harm (Rani et al. 2022). The costs of collection and reuse in other phases of the product life cycle have unknown environmental consequences. Further issues are being raised due to a scarcity of qualified experts and laborers (Whiteside et al. 2009; Ajith and Arumugaprabu 2022).

Material recovery, recycling, and reuse

In the case of green composites, biological fibers are incorporated into a matrix consisting of plants or other resin-based materials (Mohanty et al. 2000; Arun et al. 2022). In biological systems, organic macromolecules like cellulose, proteins, and starches are typically destroyed via hydrolysis accompanied by oxidation (Guiza et al. 2021). Mixing biodegradable plastics, like starch, using inert polymers, including polyethylene, with organic fiber reinforcement has received much interest because of its potential uses in plastic waste management (Joseph et al. 1999; He et al. 2000; Wielage et al. 1999; Joly et al. 1996; Li et al. 2000; Eichhorn et al. 2001; Fan et al. 2022; Ribba et al. 2022). The use of purely biodegradable composites does have several advantages: the biopolymer matrix and cellulose fibers are both fully biodegradable, as well as all waste disposal expenses are kept to a minimum (Samir et al. 2022; Jagadeesh et al. 2022).

Using and degrading naturally derived polymer polymers does not damage wildlife and does not add to greenhouse gas emissions. Based on environmental consequences, it is indeed possible to recycle biodegradable thermoplastic composites in a reasonably short time (He et al. 2022).

Plasticizers, silane coupling agents, and other additives can improve the recovery and recycling and mechanical characteristics of biodegradable composites (Hodzic et al. 2002; Wong et al. 2002: Han et al. 2022). Entirely biodegradable plastics and composite materials must be able to meet immediate market requirements (Moshood et al. 2022).

Approximately 30% of the plastics in municipal waste come from things that have been used for much less than a year and are extensively contaminated by food and organic waste. Biodegradable alternative options may be able to replace a considerable portion of the plastic waste that is challenging to get rid of or recycle (Huang et al. 2022).

Biocomposites and biopolymers are well-suited to the packaging sector, particularly for goods that are not meant to last and are prone to becoming polluted with organic waste (Patel et al. 2022).

In terms of quality and processing efficiency, green composites should compete with current plastics. Bacterial polyesters, for instance, are designed to satisfy a variety of grade and manufacturing criteria (Stepanova and Korzhikova-Vlakh 2022). All kinds of thermal products can be used to treat such materials. The esters, on the other hand, are not good enough to allow films or foils. They also have a tendency to brittleness and a loss of vapor-insulating characteristics. These limitations are likely to be solved by improving mixed formulations. One particular stumbling block is that they must comply with the criteria for certification as food-wrapping materials, which is a lengthy and expensive procedure. Since the esters are a new item, bacterial polyesters have not yet been approved for usage as a food wrapping material (Surendren et al. 2022).

At the moment, the most significant impediment is that biodegradable materials must adhere to pricing constraints. The current costs for bacterial polyesters are considerably too exorbitant for the manufacturing and packaging sectors to absorb on a wide scale, owing to the prices of raw materials and small-scale production lines (Xiao et al. 2020a, b; Kumari et al. 2022). These can be brought down to a manageable level by investment in larger units in nations with low-cost raw resources. As a result, they would be ready to satisfy the cost constraints. More consumers recognize composting as an environmentally friendly method of reusing organic matter (Chandra and Renu 1998; Yasmin et al. 2022). Recent advancements in the management of waste and plastic waste minimization have paved the way for the substantial production of sustainable composite materials (Andrew and Dhakal 2022).

Even though the bulk of organically derived and biodegradable composites cannot be used in structural applications, their use in packing and other related areas could have a beneficial environmental impact (Arman Alim et al. 2022). Reduced CO_2 emissions have the potential to renew the atmosphere and reverse any unfavorable loop of natural occurrences. If the manufacture of synthetic plastic materials is restricted to a minimum, the leftover plastic trash can be managed through reuse, disintegration, and burning without having a substantial environmental impact (Chawla et al. 2022).

Conclusions

With significant environmental benefits, green composites are replacing a wide range of materials in daily life, including metals, plastics derived from crude oil, and composites. The potential for green composites is enormous, and fresh advancements are constantly being made. However, much more study is required to create green composites with high tensile strength and high temperatures that can completely replace conventional composites while simultaneously minimizing the environmental impact of crude oil-based materials and their manufacturing processes. Green composite materials will definitely face competition from synthetic composites in the coming decades on the worldwide market. In place of fiber reinforcements, agricultural waste-derived nanocrystalline cellulose particles will be combined with a biodegradable matrix to create cutting-edge nanocomposites that are not only more durable but also more sustainable and renewable. Biocomposites are cheaper than conventional materials, are environmentally beneficial, and are composed entirely of renewable resources. The adoption of appropriate production techniques and various treatments to enhance performance to guarantee superior quality goods and services will decide the efficacy of these materials. Workability is usually determined by factors like melt viscosity, particularly specific heat, thermal transfer, and the crystalline nature of the material. In order to offer a comprehension of the suitable selection of materials and its associated manufacturing procedures, exact processing fundamental principles should be outlined. Consumption patterns will change as a result of new guidelines and laws because manufacturers will be forced to use inventive resources to address current problems and future prospects. Additionally, pre-processing methods like pre-treatment, post-treatment, biopolymer additives, and adequate drying play a crucial part in improving product quality, according to Motaung et al. (2018). Suitable and standardized fiber extraction techniques should also be taken into consideration in future research investigations in order to produce high-quality elemental fibers that can be effectively mixed into the composite matrix to eradicate fiber heterogeneity. Emerging scientists conducting research in this field, therefore, have several chances. Further research should be done on improving methods and techniques for improving the fiber-matrix interfacial properties. Additionally, the newly developed pathways ought to be able to circumvent potential issues with biocomposites produced as a result of moisture absorption, prolonged exposure to temperature, humidity, UV radiation, toxins, aging, and several types of environmental stimulation (Bao 2018). The development of biodegradability and life cycle analyses of improved biopolymers to replace petroleum-based materials is required to enable the widespread use of polymers. It is necessary to use an interdisciplinary strategy that considers manufacturing processes related to agriculture, biotechnology, polymers, and composites. Additionally, emerging bio-based polymers should be developed into lab-scale composite production techniques before they are marketed. Additionally, it is important to look into the potential applications of additional resources for the creation of novel bio-composite materials, such as leftover agricultural fibers, conventional treatments, food processing, cooking, and other materials (Gope and Rao 2016). The integration of nanofibers made of cellulose and synthetic nanofillers may be the subject of in-depth investigation, given the current trend toward the growth of nanocomposites. Additionally, problems brought on by botanical residues can be easily resolved by using them as polymer composite-reinforcing elements (Yan-Hong et al. 2015). In addition, hybrid biocomposites and plastic fabrication methods must be used (Mihai and Ton-That 2019) to improve the performance of the produced composites.

Trends for future research

Environmental scientists have seen and measured biological nitrogen absorption from soils by vegetation using nanoscale tracers. There are numerous nanosensors being developed right now that could revolutionize how we perceive our surroundings (Adam and Gopinath 2022). The possibility exists for organic nanoparticles to play a crucial role in the biological cycle. We firmly believe that as we continue to learn more about manufactured green nanoparticles, we will find that under realistic exposure settings, the majority of them do not harm the ecosystem (Mungali et al. 2022). There is no denying, however, that nanotechnology will continue to support environmental sustainability in a variety of ways. Products will perform better overall, be lighter, use less energy, and have less of an impact on the environment, thanks to nanoscale materials (Agrahari et al. 2022). There are always issues with newly developed, unproven inventions. Nanomaterials may help to clean up some ecological waste, but they may also end up polluting the environment in other ways (Behera et al. 2022). Selecting suitable nanoscale material is one of the key elements for the strategic path of nanotechnology. Understanding the potential for harm to our ecosystem from new nanomaterial-based applications is essential (Singh and Paul 2022).

More work is required to enhance the properties of recyclable composite materials, create efficient methods, and inform consumers about the advantages of reusing products (Gonçalves et al. 2022). Industries have been pressured by researchers and regulators to manufacture products using both innovative technologies and conventional materials. The production and disposal of artificial polymeric materials must coexist peacefully for the benefit of both business and the environment (Nandy et al. 2022). Biocomposites are less expensive than conventional materials and are produced from renewable resources, which are also good for the environment The trend for innovations will persist for a very long time as more bio-based composites are created and used in the products we manufacture, use, and discard (Kandachar and Brouwer 2001). The use of the proper production processes and treatments available to enhance functionality and guarantee the highest possible quality of goods and services will determine the efficacy of these materials. When considering workability, factors like melt viscosity, particularly heat capacity, thermal expansion, and crystallinity of the material are typically taken into consideration. In order to comprehend the best practices for materials and the options for related processing procedures, detailed processing core principles should be developed. It is important to look into the potential applications of agriculture, home remedies, food production, cooking, and other fiber remnants for the synthesis of bio-composites. By 2019, 8020 million pounds—a 53% increase from 2008—will be needed in the North American automotive sector in terms of lighter materials, polymers, and composites (Pervaiz et al. 2016). Lightweight materials offer a greater possibility to increase the fuel efficiency of vehicles and lower greenhouse gas emissions since decrease in vehicle weight can result in fuel savings. Additionally, lighter objects accelerate with much less effort than heavy ones. Applications of nanotechnology and nanoscience offer new methods and capabilities that can be used in environmental research (Pasupuleti 2022).

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