Received: 29 August 2021 | Revised: 21 October 2021 | Accepted: 1 November 2021
DOI: 10.1002/pc.26403

RESEARCH ARTICLE

Polymer COMPOSITES WILEY

A comprehensive review on performance and machinability of plant fiber polymer composites

Hemath Mohit[1] | Sanjay Mavinkere Rangappa[1] | Suchart Siengchin[1] | Sergey Gorbatyuk[2] | P. Manimaran[3] | C. Alka Kumari[4] | Anish Khan[5] | Mrityunjay Doddamani[6]

[1]Natural Composite Research Group Lab, Department of Materials and Production Engineering, The Siridhorn Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand

[2]Department of Engineering of Technological Equipment in National University of Science and Technology MISIS, Moscow, Russia

[3]Department of Mechanical Engineering, Karpagam Institute of Technology, Coimbatore, Tamil Nadu, India

[4]Process Eng. Tech. Transfer [PETT], CSIR-Indian Institute of Chemical Technology [IICT], Ministry of Science & Technology, Govt. of India, Uppal Road, Tarnaka, Hyderabad, Telangana, India

[5]Chemistry Department, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia

[6]Advanced Manufacturing Lab, Department of Mechanical Engineering, National Institute of Technology Karanataka (NITK), Surathkal, Mangalore, D.K., Karnataka, India

Correspondence
Sanjay Mavinkere Rangappa and Suchart Siengchin, Natural Composite Research Group Lab, Department of Materials and Production Engineering, The Siridhorn Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok Thailand.
Email: mcemrs@gmail.com (S.M.R) and suchart.s.pe@tggs-bangkok.org (S.S)

Funding information
King Mongkut's University of Technology North Bangkok, Grant/Award Number: KMUTNB-65-KNOW-03

Abstract

In recent years, the revolutionary utilization of plant fibers in polymer laminates significantly influenced environmental effects. Presently, there is progression attention in advancing bio-based materials by acquiring plant fibers from lignocellulosic components for different applications like non-structural, structural laminates, automobile components, ballistics, flooring, household utensils, and aerospace parts. These bio-based, eco-friendly components have been recognized as next-generation contestants for higher-efficacy, sustainable, cheap, environmentally friendly, and lightweight composites. Different kinds of synthetic and natural biopolymers and bio-based nanoparticles have been applied to produce sustainable materials. Bio-based polymer composites manifest unique characteristics of both eco-reinforcement and sustainable resin. This review comprehensively communicates the general characteristics and principles of nanoparticles, polymers, and their respective composites. In addition to the machining characteristics, challenges and future perspectives of the polymer composites have also been reviewed.

KEYWORDS

bio-based composites, eco-friendly polymers, machining characteristics, mechanical properties, plant fibers, sustainable materials

1 | INTRODUCTION

Polymer composites contain two or more chemical or physical distinct regions isolated from an interface.[1–3] Such different parts are comprised of a laminate with functional or structural characteristics that the independent constituents.[4,5] Polymer composites are advantageous over conventional materials for acquiring lower weight, quick installation, higher fatigue power, and corrosion resistance.[6–8] Polymer composites are generally applied in fabricating electronic devices, medical equipment, house construction, packaging, space vehicles, and aircraft frames.[9–14] Polymer composites are categorized as laminate, fibrous and particulate composites as per their kinds of reinforcement. Fiber-based polymer composites are synthetic or plant fibers, where plant fibers are termed bio-based composites.[15,16] The biodegradable resin and plant fiber create laminates termed green laminates, further organized into textile and hybrid laminates.[17–26] Hybrid laminates combine two or more kinds of plant fibers.[27,28] Most generalized fabricated laminates utilize a polymeric resin as matrix material usually attributed to as a polymeric solution. Polymer-based composite is easy to fabricate and lower cost, producing it very prominent. The utilization of non-reinforced plastics as structural materials is constrained by their bad mechanical characteristics such as impact resistance, strength, and modulus. The fiber-reinforced polymer composites are observed for specific properties like relatively cheap, higher impact resistance, better corrosion resistance, excellent abrasive strength, higher resistance from fractures, higher toughness, and specific strength.[29,30] Boron, basalt, carbon, Kevlar, and glass are applied as reinforcement in fiber-reinforced polymer composites and are broadly identified as non-structural and structural application substances.[4,31,32]

Furthermore, their non-biodegradability could share with critical environmental issues. Presently, there is developing attention of using plant fibers in polymer-based composites fabrication in different applications such as biomedical,[32–38] components for aerospace and automobiles,[39,40] packaging,[41] furniture,[42] and ballistic laminate.[43–45] Plant fibers such as pineapple, coir, bamboo, sisal, kenaf, and jute are adequate for different load-bearing applications because they possess higher resistance. Moreover, plant fibers are promoted over synthetic fabrics because they are biodegradable, renewable, and abundant characteristics that synthetic laminates cannot provide. Plant fibers can be applied as bio-based alternatives because of their benefits like lower weight, better strength, and higher mechanical characteristics.[46]

2 | IMPORTANCE OF PLANT FIBER-REINFORCED POLYMER COMPOSITES

The main components of plant fibers reinforced polymers are hydrophobic thermoset or thermoplastic matrix and plant hydrophilic fibers. Different plant fibers have been applied as reinforcement which provides rigidity and strength to the laminate. Non-biodegradable components like polypropylene, polyethylene, and polyester have been generally used as a matrix that controls and shifts the charge to the fibers.[47–50] As per the kind of matrix, plant fiber-reinforced polymer composites can commonly be categorized into two groups as entirely and partially biodegradable components. Bio-based fiber with biodegradable polymeric incorporation outcomes in the fully biodegradable composite. The addition of the conventional non-biodegradable-based resin with plant fibers turns into a partially biodegradable composite laminate: many non-biodegradable and bio-degradable plastics with their respective components obtained from these two kinds of polymeric resins.[51]

The life cycle assessment is a scientific method to determine the environmental influence or constituents throughout their life cycle. It outsets from the addition of natural compounds to fabrication, final disposal, recycling, utilization, and treatment at the end of life, known as the cradle to a grave method.[52–54] The lucintel record forecasts that the world material for plant fiber composite substances will expand at a component total growth rate of 8.2% between 2015 and 2020. The primary movement for developing this market is incrementing a claim for environmentally friendly and lightweight laminates for different applications, for illustration in construction, automotive, and other fields.[55] The automobile companies are growing to the highest component total growth rate in the plant fiber composite market. The principle behind the development of the automobile sector is the increment in population and the improvement in the public's disposable income. The public acquires more inventions in automotive by implementing functionality, comfort, and style. Because of the high benefits and better characteristics of plant-based fibers over synthetic fabrics, academicians and scientists get noticed toward the plant fibers. The primary factors affecting the mechanical properties of plant fiber-reinforced polymer composites such as selection of matrix material, selection of yarn (fiber concentration, processing, aspect ratio, kind of fiber, extraction technique, and yield time), porosity, fabricating designs of laminates, interface strength, fiber alignment and scattering.[53,56,57] The mechanical and physical characteristics of renewable bio-based fibers differ from fiber to fiber;

components incorporated with abaca exhibit higher mechanical characteristics among different bio-fibers like sisal, jute, rice husk and abaca.[58]

Flexural characteristics are excellent for sisal and jute hardness.[59] Hybrid plant fiber-reinforced composites present higher strength characteristics like excellent resistance from impact load, shear, tensile, and bending elements than glass fabrics reinforced laminates alone under different forces.[60,61] Plant fibers such as dates, shells, rice, sisal, kenaf, coconut, jute, and components obtained from organic waste, palm oil, and sugarcane play a critical role in influencing the tribological characteristics of resin components reinforced with plant fibers.[62,63] Parameters like fiber surface modification and their orientation and proportion of fiber volume affect the plant fiber-reinforced polymer composites.[64] Polymer laminates with constant banana fiber as a reinforcement to the polymer where the coupling agent is modified with maleic anhydride, which can be applied for different applications like construction fields, sporting goods, aircraft, and automobile parts.[65] Modification performed with chemicals enhances vibration properties of plant fibers of banana and sisal fibers incorporated with polymeric components. The gratitude to the enhanced chemical transformation technique enhances the interfacial bond within the matrix and the reinforced material.[66] Composites' thermal, mechanical, and acoustic characteristics increased with betel nut fibers based on the surface modification of fibers because of polar interactions and higher adhesion under fiber interfaces.[67]

3 | ECO-FRIENDLY POLYMER COMPOSITES

Because of excellent sustainability and biodegradability characteristics, eco-friendly polymer resins have been established in advanced materials.[68,69] Bio-based resins like chitosan and collagen have been applied to produce hybrids possessing improved mechanical and morphological characteristics.[70,71] The advancement of synthetic resins likes polyvinyl chloride and polystyrene has affected the environmental issues outstanding to non-removing behavior.[72,73] Subsequently, eco-friendly polymers have been examined as petroleum-based resin alternatives. The resin from the classification of polysaccharides and proteins-based biodegradable components has been applied.[74,75]

Furthermore, several eco-friendly synthetic resins were modernized. An essential division of eco-friendly resin is polyesters; this division contains polyester amide, polylactic acid, polycaprolactone (PCL), polyhydroxyalkanoate (PHA), and other polyester-based components. The PHA-based polyester has been established from the petrochemical method.[76,77] This polyester contains micro thermoplastic possessing accurate mechanical characteristics. The PCL has been hired as an essential eco-friendly resin. The PCL has been produced from a ring of caprolactone. It is a semi-crystalline and hydrophobic resin. Polylactic acid is one of the thermoplastic bio-based resins with improved mechanical characteristics.[78] These polymer matrices can withstand bacterial or microbial attacks.[79] From bio-based components, green resins have been produced from enzymes. The polyesters like PCL and PHA have observed potential utilization in bioimplants and packaging applications.[80] The PCL has also been applied in bio-based components, tissue engineering, and drug delivery.[81]

3.1 | Sustainable nanofillers

Sustainable-based polymer nanolaminates must be established from ecological nanoparticles.[82] The necessity for bio reinforcement attains because of the non-toxicological and non-hazardous impacts of nanolaminates on the environment.[83] The incorporation of bio-based nanoparticles in bio-resins achieves the expected sustainable effects of these nanolaminates. The modification and preparation of ecological nanoparticles have also been employed. The bio-based nanoparticles do not influence the favorable fabrication and transforming methods. Silica nanofillers have been reinforced in bio-based nanocomposites.[84] Silica nanoparticles have been applied to improve the strength of nanolaminates. Resin and nano-clay bio-based nanolaminates have been produced from melt blending, in-situ polymerization, and solution methods. Generally, lower nano-clay concentration may enhance the fabricated nanolaminates' physical characteristics.[85] Nanotube (Halloysite) is an essential kind of bio-based nanoparticle.[86] These nanotubes acquire the aluminosilicate structure of nanoclay. In nanolaminates, these nanotubes have been applied to improve the mechanical characteristics, surface hydrophobicity, and uniform distribution of nanofillers.[87,88] The cellulose nanoparticles and nanofibers are also essential bio-based nanoparticles.[89] The cellulose nanofillers have been collected from extracts of a plant from chemical or ultrasonic treatment techniques. Starch-based nanofillers have also been applied as eco-friendly nanoparticles to produce nanolaminates.[90] The reinforcement of starch in nano-components has been used as a chemically and newly modified structure. Efficient bio-based nanoparticles have been employed from soy protein.[91] Plant fibers like bamboo, zein, jute, bagasse, etc., have also been applied as bio-based nanoparticles.[92]

Graphite, graphene, and their respective carbon-based constituents have been involved as biodegradable particles. These nanofillers have been used to produce robust, conducting, and lower-weight nanolaminates. Many other viable carbon-based nanoparticles like carbon nanotubes, graphene, and so on, were also attracted.[93] The thermal, mechanical, electrical characteristics and manufacturing methods for carbon-based polymer nanolaminates have been applied for higher performance.[94] The eco-friendly nanolaminates depend on the carbon-based nanoparticles involved in catalytic, packaging, and piezoelectric sensor application.[95,96]

3.2 | Bio-based polymeric nanolaminates

Well-established eco-effective resins are polyethylene glycol, polyurethane-urea, polyethylene oxide, and polyurethane.[97,98] These ecological resins are generally collected from bio-preparation methods. The eco-effective resins are encouraging components for a range of biomedical applications, coatings, adhesives, drug delivery, and membranes. Montmorillonite (MM) based nanoclay exists in the phyllosilicate region of materials. MM component has been examined as an eco-friendly nanoparticle. The nanoclay has been applied as reinforcement to nanolaminates owed to cheap, higher aspect ratio and more excellent surface are. The conducting nanoclay platelets may expedite the uniform distribution in polyurethane and other bio-based polymer resin.[99] The nanoclay reinforced polyurethane-based polymer nanolaminates have barrier characteristics, heat constancy, and higher stability from a chemical reaction. Bio-based nanolaminates of elastomeric cloisite and polyurethane have been observed.[100] Nanoclay particles play as bio-based flame retardant nanoparticles for biodegradable polymer. Graphene oxide and graphene nanoparticles are also eco-effective.[101] The addition of graphene oxide in polymers may improve bio-based nanolaminates' mechanical, thermal, and electrical characteristics. Vieira et al.[102] fabricated graphene oxide and MM reinforced polyurethane nanolaminates. The polyethylene glycol-based resin was also comprised of these nanoparticles. The rheological and structural investigations were conducted to examine the possibility of these eco-friendly components. At the same time, polyvinyl alcohol (PVA) is a water-based synthetic green resin. Morsi et al.[103] produced carboxymethyl cellulose (CMC) and PVA-based eco-friendly components. The CMC/PVA was also incorporated with gold nanofillers. The gold nanofillers was separated the leaf extract of mint using the bio-fabrication technique. Transmission electron microscope (TEM) morphology of gold nanofillers and nanolaminates are given in Figure 1.

The pure spherical gold nanofillers mean size from 5 to 29 nm, whereas the CMC/PVA and gold nanofillers nanolaminates are observed as in the shape of hexagonal or triangles.[104] The adjustable dielectric permittivity and conductivity of the bio-based materials are adequate for possessing microelectronic equipment. Kumar et al.[105] produced bio-based nanolaminates of polyvinyl pyrrolidone or chitson mixed incorporated with cellulose nanofiller (9–11 nm and 100–200 nm of diameter) length, respectively) separated from jute fibers. The bio-based nanolaminate components were fabricated from the solution casting technique. The parts have a barrier, thermal, renewability, mechanical, and accurate biodegradability characteristics for food packaging application.

Polylactic acid is a bio-based aliphatic thermoplastic resin collected from sugarcane or starch. Chieng et al.[106] reinforced graphene nanoplatelet in epoxidized palm oil and PLA mix. The tensile characteristic of the bio-based nanolaminate was improved with graphene nanoparticles loading. The PLA-based components were adequate for biomedical and packaging applications. In comparison, the starch is a bio-based resin possessing lower melt viscosity, accurate gas permeability, and brittleness. This bio-resin has been applied in broad-ranging eco-friendly applications.[107] The nanoparticles reinforcement incorporation has been evident to improve the existing characteristics of the starch matrix. Cao et al.[108] homogeneously dispersed hemp cellulose nanofibers in a starch matrix. Incorporating the cellulose nanofibers in starch improved the water resistance and mechanical characteristics of bio-based packaging components.[109] Kang et al.[110] applied an eco-friendly latex co-agglomeration method to collect graphene oxide and carboxylated acrylonitrile rubber (XNR) based bio-materials. The graphene oxide/XNR nanolaminates have observed higher gas barrier and mechanical characteristics for packaging applications. Figure 2 exhibits the interaction and hydrogen bonding within the graphene oxide nanosheet and XNR matrix. Minimum 1.9 vol% of graphene oxide concentration was essential to employ the interactions within the nanoparticle and matrix. Figure 3 explains the swelling proportion and nanolaminates were observed beneficial for flame resistance environmentally friendly packaging applications. Subsequently, the distribution of ecological nanoparticles collected from renewable sources in the bio-based resin may clear new prospects in the sustainable advancement of eco-effective components.[86]

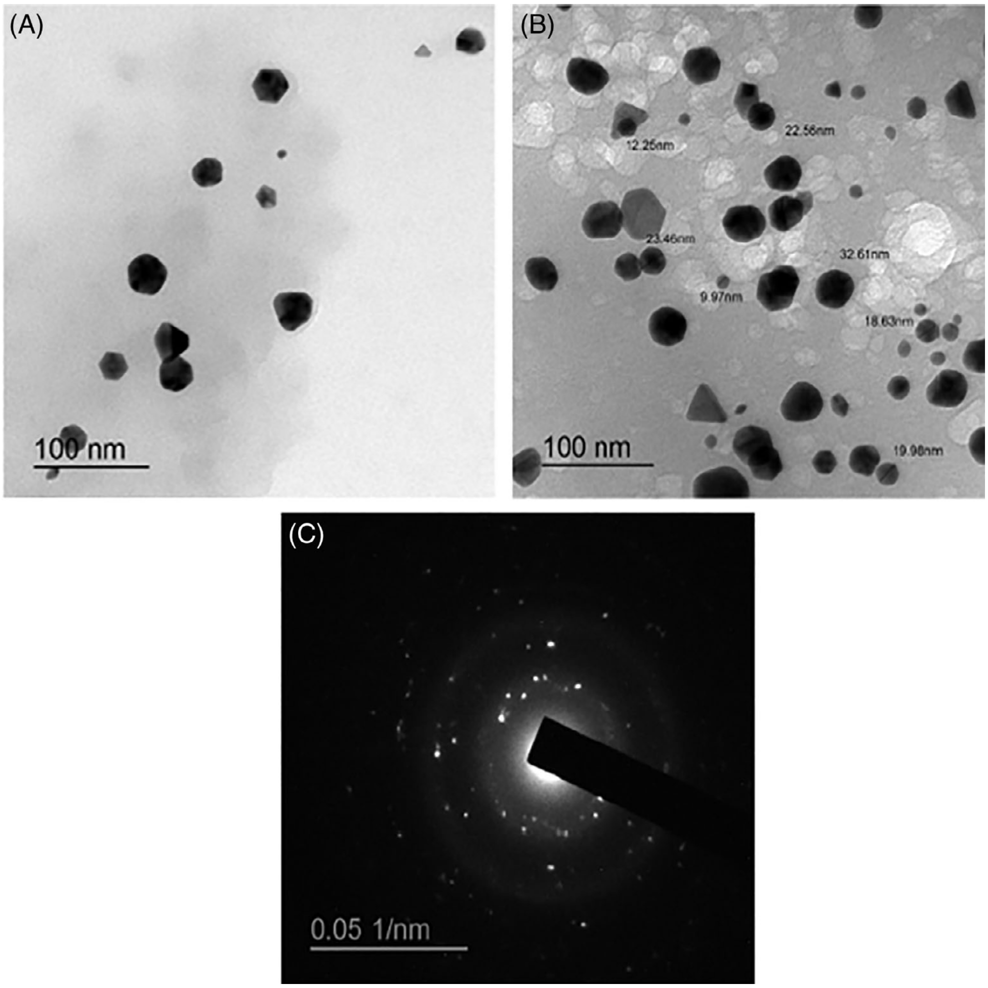

FIGURE 1 Transmission electron microscope micrographs (A and B) particle size distribution of gold nanoparticles, and (C) the electron diffraction pattern for gold nanoparticles (Reproduced from Elsevier, license no. 5125431080820)[48]

4 | LAMINATES AND FABRICATION FACTORS

Massive investigations have expressed many parameters affecting plant fiber laminate mechanical and physical characteristics. The parameters contain fabrication factors like time to hold, rate of temperature, processing method, pressure level, and so on, and laminate factors like many layers in composite, fiber orientation, the concentration of fiber, type of reinforcement, sequence of stacking, quantities of reinforcement, and sources of fiber. Plant fibers are well established for hydrophilic behavior, created in a scheme of fiber from the hydroxyl regions. In this context, the polymers are generally hydrophobic. Hence, the mixture of these components is not adaptable because of the non-uniform distribution of fiber in the polymer and the weaker interface between matrix and fiber. Fiber modification is one method for improving interface adhesion between the plant fiber-polymer matrix, chemical bonding, and surface area.[111–120] The influence of chemically modified flax and aloe vera immersed in 10% of NaOH (sodium hydroxide) and 5% of KMnO4 (potassium permanganate) for 60 min and reinforcement with barium sulfate ($BaSO_4$) was investigated from Arulmurugan et al.[121] The fiber sequences for the laminate sample were conducted from the wet layup method, and the mechanical properties of fiber-reinforced epoxy resin laminates were studied. The outcomes exhibited that the tensile characteristic of the laminate containing four fabric layers of flax improved with the incorporation of barium sulfate because of fiber chemical surface modification, a good combination of filler and polymer resin, and enhanced interlacement in the flax fiber, which produced interconnection in the structure of fibers within the matrices. This laminate structure exhibited a greater strength because of the denser mat scheme of the flax fiber.

Furthermore, laminates with alone aloe vera fibers without any treatment from barium sulfate leads to higher impact strength. This kind of laminate consumes the energy of impact, effectively assigned to the aloe vera fiber's adaptability. In another investigation, Morris

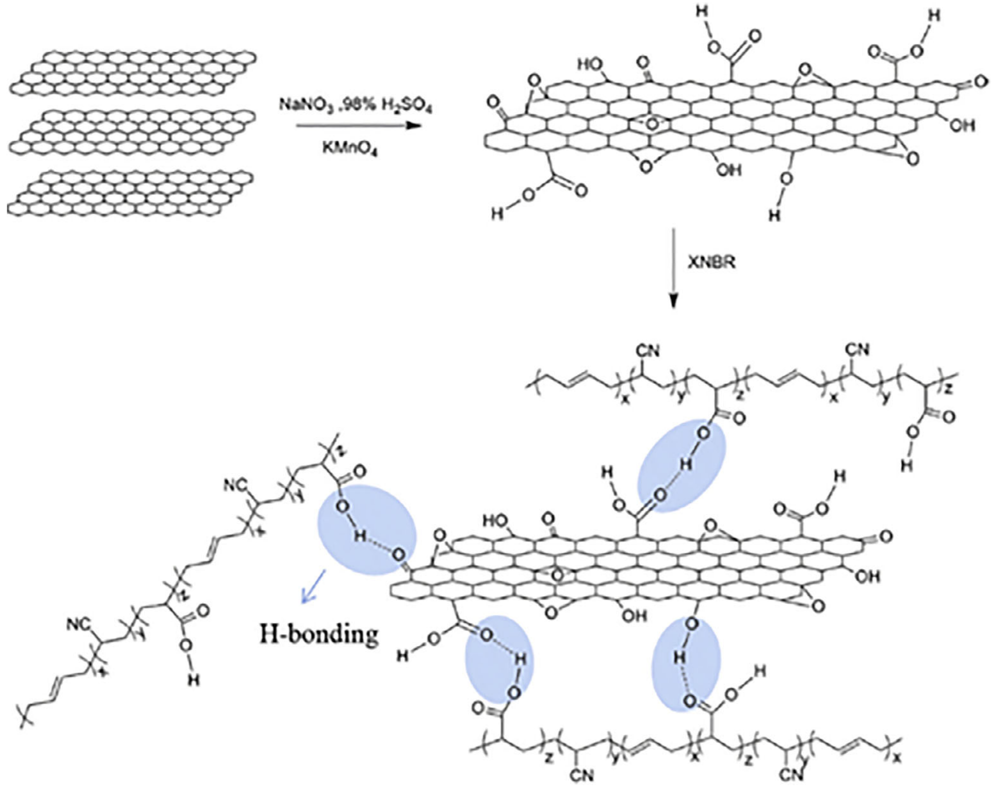

FIGURE 2 Schematic representation of hydrogen bonding interaction between graphene oxide and rubber (Reproduced with permission from Elsevier, license no. 5125440949825)[101]

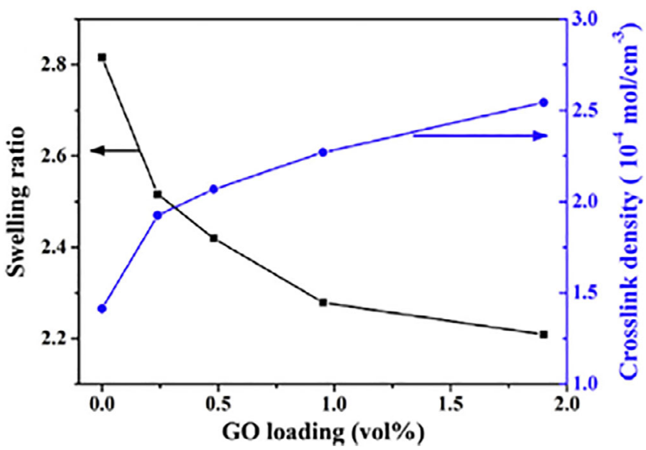

FIGURE 3 Swelling proportion and cross networking density of graphene oxide/rubber with different concentration of graphene oxide (Reproduced with permission from Elsevier, license no. 5125441359842)[101]

et al.[37] exhibited the implications of utilizing the solution of NaOH to modify the surface scheme of bamboo, lyocell, silk, and cotton as an outcome of immersion time on the mechanical characteristics of the medicinal utilization of the epoxy-polymer-based laminate. Figure 4 exhibits the contour of the surface and microstructure of fiber after being modified with sodium hydroxide for 5 min, 2 min, and 30 s of soaking time to determine polymer resin progression over time. The emerging characteristics of composites were observed to have a lower effect on the structural modification of the laminates. Furthermore, the chemical surface modification did not evident that the final fabricate composite had enhanced the microstructure or strength of the laminates.[122]

Awais et al.[123] studied plant fiber laminates reinforced with flax, hemp, and jute fibers using the compression molding method in polypropylene polymer. Three different fiber structures were fabricated: flax, hemp, and jute yarns like knitted, woven commingled, and woven fabric. They examined the impact and shear strength of the hybrid laminates structure of the fabric. The outcomes signified that shear strength was improved for all kinds of plant fibers in the knitted laminates compared with woven and their commingled laminates. Furthermore, attracting conclusions were collected, where woven laminates displayed enhanced performance in terms of impact resistance compared with knitted and woven commingled laminates devoted to the wings of the fiber woven scheme and the interlacing design that enhanced the damage resistance characteristics of woven composites. The impact of hybridization of carbon and flax fabrics produced from vacuum-supported polymer admixture on the tensile strength and modulus was observed from the Kureemun et al.[124] There were five kinds of hybrid carbon-flax sequences of stacking incorporated with epoxy resin. The outcomes of their

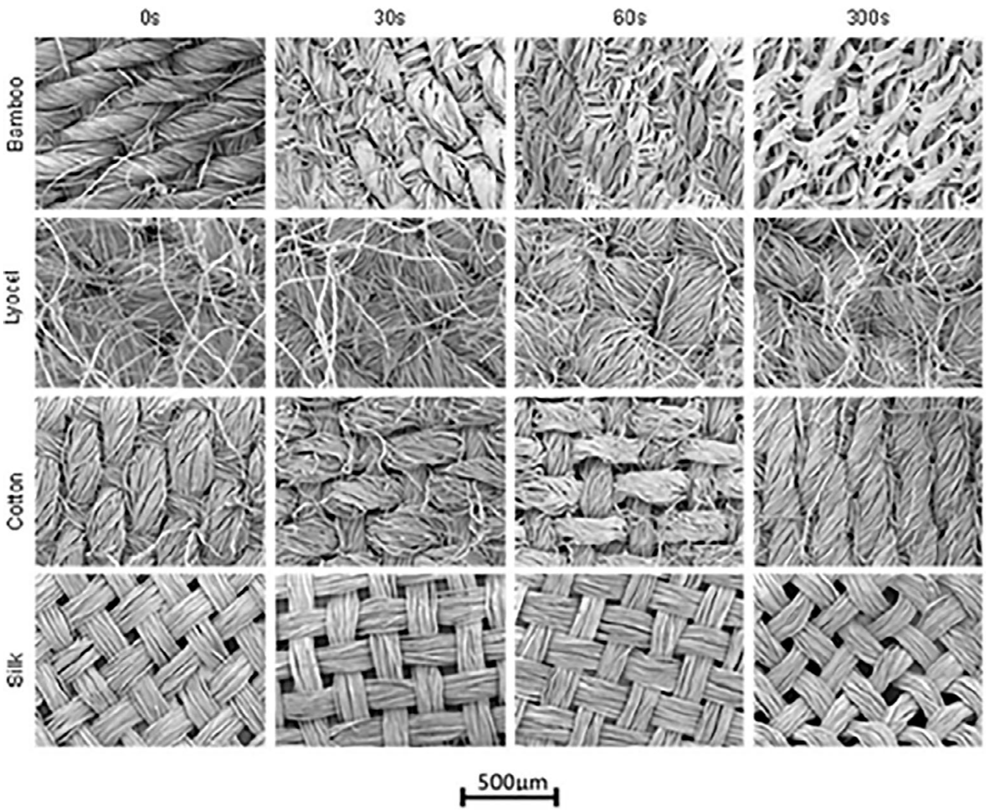

FIGURE 4 Microstructure of the woven cotton, silk, bamboo, and lyocell after soaking in sodium hydroxide solution for different time intervals (Open Access Journal)[35]

observations exhibited that the tensile characteristics of the multi-carbon fabrics hybrid laminate with a flax layer enhanced tensile cohesion by locating the fixed carbon fabric layers and excellent structural crinkles within the fabrics of carbon and flax. Torres et al.[125] fabricated flax and jute fabric laminates in an array of geometrical and material configurations, with the target of regulating statistical dispersions of mechanical characteristics. The laminates were manufactured from a vacuum-coupled resin transfer molding process with epoxy polymer. Many weave schemes were chosen; specifically satin, twill, and plain and geometrical contour for continuous fiber were in the directions of ±90, 0°. A statistical examination of the failure strain, strength, and elastic modulus of the laminates for fabrics exhibited that the laminates of both fabric kinds were higher than the random agreement because of the power of the fiber in the loading position.

Furthermore, compared with flax laminates because of fabric crinkles in the structure, the strength of continuous flax with ±90, 0° positions was observed more remarkably. Yallew et al.[126] examined the influence of fabrication factors on the tensile properties of woven sisal, jute, and hemp reinforced polypropylene (PP) laminates, specifically the pressure and heating temperature. From the compression molding technique with three different pressures (0.5, 1, and 1.5 MPa) and temperatures (165, 175, and 185°C), laminate samples were produced under the constant rate of 4 min as curing time. They observed that laminates fabricated from woven sisal under the pressure and temperature of 1 MPa and 175°C, respectively, had the highest tensile properties compared with other cases. Sivakumar et al.[127] fabricated glass and kenaf fabric laminates from different fiber combinations as stacking sequence and polymer kinds like epoxy and polypropylene. In this investigation, polypropylene-based hybrid laminates were created from the hot press compression molding technique, where epoxy-based hybrid laminates were fabricated using a vacuum-supported infusion method. Hybrid bio-based laminate fatigue and tensile strengths, where the microstructure of the damage samples was estimated. The fatigue and tensile strength were enhanced with the increasing quantities of glass fabrics in the polypropylene laminate but decreased weariness under lower loads. The fatigue strength emerged to be significantly improved with epoxy polymer as a reinforcement material compared with the polypropylene for a similar fatigue cycle. For the polymer utilized, laminate with fabric combination glass-kenaf-glass reinforced in polypropylene concluded in most considerable specific fatigue strength than the laminate reinforced with epoxy polymer. In comparison, the fabric combination of kenaf-glass-kenaf, the higher fatigue strength under lower load was also observed in the polypropylene-based laminates.

5 | FLAME CHARACTERISTICS OF POLYMER COMPOSITES

One of the components with terrific possibility for distinct industrial and domestic stocks is plant fiber-reinforced polymer laminate. Furthermore, its elements, which contain cellulose and polymer, are highly flammable. In this context, this problem is being massively considered by investigators throughout the world. The coconut fiber incorporated polypropylene laminate for automobile interior panels is being investigated by Ayrilmis et al.[128] A similar investigation examined the laminate panel's physical, mechanical, and flammability characteristics. The four ranges of coconut fiber concentrations were blended with a coupling agent, polypropylene powder, and 3 wt% of maleic anhydride grafted polypropylene particles. The rising ranges of coconut fiber considerably influenced the laminate's water resistance and internal bond strength. Outcomes exhibit that the optimum laminate panel function for automotive interior uses combines 60 wt% of coconut fiber, 37 wt% of polypropylene particles, and 3 wt% of coupling agent. Before adding the polymer, the coir fibers were first chemically modified with sodium hydroxide, followed by ensilage. The unmodified fibers laminate is offered as a regulation. To decrease the laminate's flammability, the basilisk, a phosphate kind of flame retardant, was reinforced into the laminate. The amount of Draco attained the hindering oxygen index and burning features of the modified and unmodified laminates.

The effect of coupling agent and flame retardant on the achievement of oil palm reinforced polypropylene laminate.[129] To develop laminate using the melt casting method, alkali modified and unmodified fruit bunch fiber were mixed in polypropylene with and without the magnesium hydroxide and maleic anhydride as a flame retardant. The design of the laminates was performed using a mechanical and burning test with a scanning electron microscope (SEM) and Fourier transform infra-red (FTIR). The considerable improvement in flame retardant characteristic was around 60 vol% of chemically modified fruit bunch fibers reinforced in polypropylene laminate with a coupling agent. The development of enclosing texture examined the improved mechanical property; the flammability of plant woven coir tree leaf sheath incorporated phenol-formaldehyde laminates were studied.[130] The coir laminates were produced in modified and unmodified forms under the volume proportion of 40 wt% of phenol-formaldehyde polymer and 60 wt% of the sheath. 5% of sodium hydroxide was applied to chemically modified coir fiber. A hydraulic press was used to produce a laminate panel around 14,000°C. The underwriters' laboratory test and restricting oxygen index were applied to estimate the laminate's flammability. Depending on the outcomes of the flammability test study, there was a growth in decrement and flame resistance in the flame propagation rate and weight loss for modified fibers. During the restricting oxygen index study, the unmodified alkali laminates needed lower oxygen than the modified laminates to burn. Independently, the flammability of laminates applied for construction and decoration will be improved from the treatment of coir fiber.[131]

6 | MACHINING OF NFRCS

The polymer composites are heterogeneous (material characteristics range from location to location), and isotropic parts are independent of position. Hence, the preparation of laminates produces issues when compared with the processing of conventional materials. However, the abrasive behavior of the synthetic fabric affects the damaging of the cutting tool and rough finish that can affect the tool in terms of damage.[132] In machining laminates, there is no formation of chips. The material deportation principle is potentially more significantly defined as cracking, rather than discharging the component, the effect of rigid fibers damaged edge. In this context, the cut edge endures appreciable abrasion, which tends to brisk wear.[133]

The specific issues contain framework machining of compound structure and tools selection for rigid sectioning materials. The synthesis of a laminate is mainly based on the relative and properties of a resin matrix and reinforcing components and their feedback to the machining method. However, the aggregation of that particular method always awaits on the mentioned characteristics: safety and environmental considerations, clarification and fund requirement for new machines, kind of work, piece shape and dimensions, availability of internal technology, the number of components, precision, and finishing requirements, current work practices, the appliance of cutting tools and the right equipment.[134] Machinability indicates the advantage of regularly machining a material, eliminating the fibers with a satisfying end under a lower value. The workability of the laminate is based on the polymer matrix and the type of reinforcement.[135] The attributes of the reinforcement applied will calculate the ability to machine the polymer composites. The cutting loads generated during the polymer laminate machining frame affect the scheme of deficiencies. A quantity of the damages is the breakout of fiber, cracking, cracking, and fiber pulls out from the polymer matrix, the production of voids, cavities, and small holes within the polymer matrix.[136] The output factors investigated as a workability degree are the beneficial lifespan of the tool, wear of tool, roughness of an external and internal surface, power, torque, delamination problem, and cutting forces.[137] It is observed that the literature is based on the machinability of the plant fiber-reinforced polymer composites in terms of machining power, specific cutting pressure, surface roughness, and material removal rate that is lower than the machinability of fiber-reinforced laminates.[138] The machinability of plant fiber reinforced polymer composites is broadly indicated from the fiber orientation, kind of fibers, polymer type applied, and their thermal and mechanical characteristics. The examination of failures and damages correlated with the synthesis of bio-based laminates will support choosing the optimum case for manufacturing and the optimum weight fraction of laminate to enhance the workability.[139] Plant fiber-reinforced polymer composites' restricted workability is needed for interlocking between the fiber and polymer matrix. The fiber must be chemically treated to develop adhesion and enhance the laminate's workability to prevent this.[130] Other parameters which affect workability are the sample material, tool geometry, material of tool, and processing conditions.[139,140]

6.1 | Non-traditional machining

Because of the eco-friendly and sustainable behavior, the request of plant fiber-reinforced polymer laminates increments in different applications like household utilization, tool and die making, precision engineering, aerospace, and automobiles.[141] The machining from the traditional method produces long-lasting issues like lower productivity, insufficient surface roughness, and fiber pull out because of their intermolecular scheme. In the context of cutting tool specifications, the machining of fiber-reinforced polymer laminates is an imposing method.[142] The machine tools with higher hardness, toughness and positive rake are prescribed to attain an excellent surface finish. The materials of tools that can accommodate are only a restricted selection.[143] Also, traditional methods develop further decays in the form of gas, liquid, and solid that outcome in critical environmental and occupational health problems during machining. Thus, eco-friendly non-traditional machining techniques are essential.[144] Many innovative metal cutting methods generated in the past years are a significant accomplishment compared with the past decades. A comparable advancement has appeared with the machine tools and power sources methodologies. A new fabricating technique, also termed non-conventional methods relevant for component joining, forming, and removing, is also proposed to meet the complexity of machine components. In the machining of plant fiber-reinforced polymer laminates, some investigations attracted conventional techniques than non-conventional processes. The non-conventional machining techniques for plant fiber-reinforced polymer composites include laser beam machining, electric discharge machining, ultrasonic machining, and abrasive water jet machining.[145] The machining of bio-based polymer composites in ultrasonic and electric discharge machining because of non-conductive characteristics, lower hardness, and more flexibility.

6.1.1 | Abrasive water jet machining process

Sustainable fabrication is an essential condition to be employed by all manufacturing engineers, not because it is a trend but because it requires a constraint to the world we alive. Traditional machining produces many problems like surface finish, delamination, and fiber pullout.[146] From this part, the dirt developed during the conventional machining method have environmental and health problems. Bio-based fabrication is the renewal of manufacturing techniques and the development of eco-friendly methods between manufacturing and production.[147] Many investigators studied the machining of polymer laminate from Abrasive water jet machining but some scientists on the machining of bio-based laminates. Abrasive water jet machining is one of the generally applied non-conventional machining applications. In this context, non-traditional and traditional machining techniques, abrasive water jet machining can work on all engineering materials like rocks, glass, and ceramics, regardless of material thickness and characteristics.[148] Abrasive water jet machining becomes the unique machining method, precisely where precision must be controlled. While machining polymer composites, abrasive water jet machining methodology has attained extensive examination from managements due to their particular benefits like higher productivity, small cutting forces, lower wear of tool, thermal damage, and lack of heat-activated zone.[148] The abrasive water jet machining is a growing machining technique in that a high-speed jet of abrasive slurry affects the water's surface. It eliminates the component depending on the erosion mechanism.[149]

The water in the jet operates as the coolant and performs both the eroded and abrasive elements to clear the effort. The pressure of mostly 400 MPa is used to produce the water jet. It is evacuated using a diamond nozzle to have an accurate water jet under the velocity that meets 900 m/s.[150] Figure 5 exhibits a general abrasive water jet machining scheme.[151] Even though abrasive water jet machining is the most essential and efficient machining technique for polymer laminates, its characteristics are based on many methodological parameters like mass

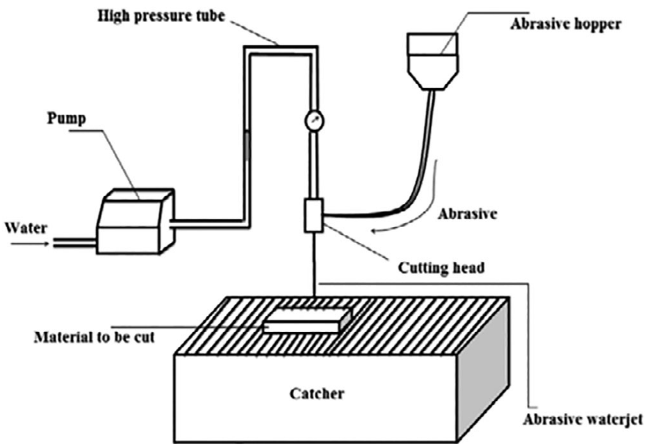

FIGURE 5 Schematic of abrasive water jet machining (Open Access Journal)[141]

flow rate, size, and type of abrasive, work material, hydraulic pressure, and distance of nozzle.[152]

6.1.2 | Laser beam machining

The laser beam machining is a non-traditional technique that provides an exciting substitution to all other non-traditional techniques because of abrasion less method that removes deviation of machine tools, tool wear, cutting forces, vibrations, and non-contact. It can be suitable for all kinds of components because of its lower price, end-product quality, short processing time, and laser cutting of laminate has broad applications in companies. The laser machining process utilizes a directional coherent monochromatic beam and higher energy attracted on a short position of around 1.0 mm diameter. This vaporizes and melts the component through the bottom. The laser beams are broadly applied for sintering, welding, heat treatment, marking, drilling, and cutting.[151] Figure 6 exhibits the diagram of the laser beam machining.[153] There are many benefits over conventional machining; laser machining is suggested for fiber-reinforced polymer laminates. Laser cutting is a thermal technique and is not affected by the hardness and strength of the material. Hence, it is excellent for heterogeneous machining components comprised of distinct regions with contradictory mechanical characteristics.[154] It offers flexibility to cut rigid structure, thin kerf width, and higher machining rates. The kind of laser to be applied for machining a laminate based on the material characteristics. There are two types of lasers used in the industries as CO_2 and Nd-YAG laser were generally applied for cutting polymer laminates. The CO_2 laser is managed in a continuous medium. It can be applied for cutting glass fabric reinforced laminates, whereas the Nd:YAG laser is performed in a pulsed medium applied to section metal matrix laminates.[155] The effectiveness of the laser beam machining is based on the capability of the component to consume the energy emitted from the laser beam.[156]

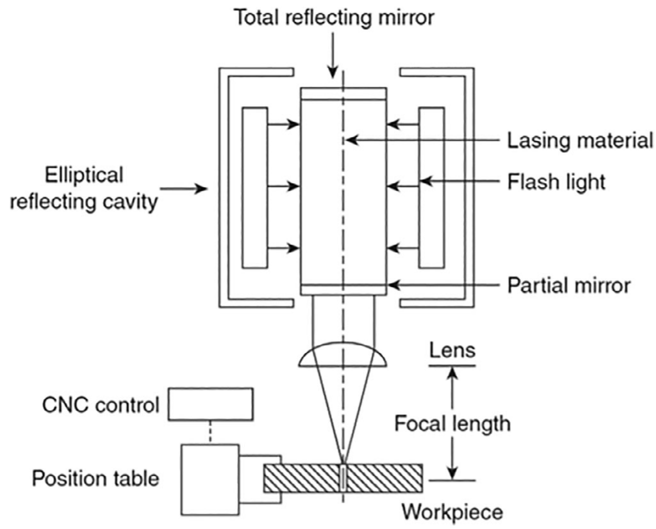

FIGURE 6 Schematic of laser beam machining (Reproduced with permission from Elsevier; license no. 5125730382729)

6.2 | Traditional machining

6.2.1 | Drilling of fiber-reinforced composites

One of the most feasible techniques of producing a component is drilling. The cutting has holes in metals, boards, and other parts. The main feature that categorizes it from other methods is the extrusion and collective cut of metal on the corner and center of the drill. The drill is pressurized against the sample and swirls at 100–1000 rpm. This loads the sectioning edge against the sample and sectioning off-chip from the dent.[157] It is a more beneficial method than other fabrication methods. The parameters that influence drilling functions are drill geometry, feed, material characteristics, and spindle speed.[158] A drill is a complete cutting tool or machine with a chisel or reciprocating hammer applied to create dents. It has more cutting slots for passing splinters and liquids to be lifted. The drill contains tip, body, and peak.[159] The aspect of the worked sample calculates the efficacy of the bolted rivets or joints.

Furthermore, certain features of polymer laminates, such as extreme abrasiveness of fiber, anisotropy, inhomogeneity, and layered structure, are significant problems for machining conditions. The factors like cutting velocity, tool material, feed, and tool geometry affect the quality of the hole.[147] Compared with the synthesis of metallic components, the laminate presents a sequence of failures motivated by processing like cracking, chipping, fiber extraction, bridging, damaged surface, and polymer delamination. The input factors impact the drilling parameters or output factor in the polymer laminate drilling.[160]

6.2.2 | Milling of plant fiber-reinforced polymer composites

The exceptional flexibility, the process of milling is one of the most common machining methods. This component elimination technique can produce an assortment of characteristics in one element by sectioning off waste material.[161] Milling is applied as a final machining method to create high-quality designated surfaces like three-dimensional surface contours, slots, holes, and pockets.[162] Milling is also used as a machining process of fiber-based polymer laminates because of the abrasive behavior of the materials, anisotropic, and non-homogeneous, where these components are difficult to machine. The kind of fiber, volume proportion of the resin, and reinforcement structure are essential parameters that control the processing factors and tools selection. During milling plant fiber-reinforced polymer composites, the friction and contact actions within the laminate and every cutting tooth of the milling possess shearing and rotation of the fiber. The higher fiber rigidity permits simple shearing of the filler in laminates reinforced with plant fillers.[163] Several scientists are presently ongoing on machining synthetic fabric laminates in specifically the milling process of polymer laminates. In modern organizations, plant fibers have compensated substantial interest to networking unreal fibers like carbon and glass fabrics.[147] The CNC and traditional machines have been utilized to mill plant fiber-reinforced polymer composites. The standard milling tends to a deviation in the durability of the machine part because of damage like burning of a polymer matrix, micro-fractures, delamination, and fiber separation, which conclusively affect modifications in laminate durability.[164,165] Many investigations also concentrated on milling to upgrade the production time and surface finish.[166]

6.2.3 | Turning of plant fiber-reinforced polymer composites

As discussed above, the plant fiber-reinforced polymer composites have broadly applied in different sectors like bridges and structures in terms of civil infrastructure, offshore platforms, helicopters, cruisers, airplanes, vehicles, spaceships, and sporting belongings. Hence, it is crucial for fabricating significance on prospects of plant fiber-reinforced polymer composites processing and workability to attain satisfactory work performance and higher product quality. Plant fiber-reinforced polymer composites' workability and machining characteristics are logically inconclusive compared with a traditional metal cutting process.[157] The methods like drilling, milling, and turning must retrieve the surface finish and the simplicity of joining and assembling surfaces. Many scientists investigated processing composites from metal matrix composite, glass fiber, and carbon fiber reinforced polymer composites.[122,167] Still, the previous investigation examined that it did not pursue hard work to change the plant fiber-reinforced polymer composites. The turning process is a machining technique that includes eliminating waste components of the surface to collect the required surface quality and dimensions from a single-point cutting tool. The turning method contemplates different pressures like cutting depth, speed, and feed rate as machining factors. Polymers, composites, and metals are used as work components, tool geometry, and material as cutting tool factors.[168] In-plant fiber-reinforced polymer composites, only a few investigations are present. Zajac et al.[169] identified the effect of feed and rotation speed on the surface roughness during turning in wood polymer composites. The outcomes exhibit lower feed rates, higher cutting velocity, and the tooltip radius suggested for processing this component. The homogeneity of the wood polymer composites is decreased from uniform wood flour or by incrementing the quantity of coupling agent. Sivakiran et al.[170] investigated the effect of the factors like cutting, feed, and velocity on the surface irregularity and metal removal rate during the traditional processing of hybrid polymer laminate reinforced with randomly oriented short banana fibers. The design of the experiment was conducted with the response surface technique.

7 | CHALLENGES AND FUTURE PERSPECTIVES

From industrial innovation 4.0, the advancement of plant fiber-reinforced polymer laminates prevails in severe problems. The polymer laminates are generally manufactured with thermoset polymers because these laminates are well-established for their higher strength.[171] Furthermore, the manufacturing techniques in a novel method are barely ever recorded. The additives fabrication anchorage the three-dimensional printing process from a thermoplastic matrix, ceramic to metallic components. It decreases energy utilized, labor monitoring, and waste components.[172] The infusion of plant fibers reinforcement in yarn structures and particles in polylactic acid polymer laminates were observed as selective laser sintering or fused deposition modeling 3D printing components.[173] Regrettably, no medium is present for woven plant fibers laminates in the additives fabrication to date. As per the future perspective, woven plant fibers should be included in additive manufacturing to create rigid laminate under the minimum price. Even though an intense investigation was performed on woven plant fiber laminates, the utilization of woven plant fiber in internal aircraft parts is not observed yet. Aircraft parts have strict control over their performance and durability, specifically flame retardancy.[174]

Furthermore, woven plant fibers operate similarly to wood components with lower thermal stability and higher flammability in standard.[175] Even though many modifications and flame-retardant materials were involved in the woven plant fiber laminates scheme, improved flame and thermal characteristics were attained. However, conformity with aviation components needs implies still challenging. Hence, presuming the woven plant fiber laminates as the different aircraft internal components would be the previous method required to be performed rather than ongoing investigation without commercialization. As commercialization is an element of the future state, the generalization of woven plant fiber laminates is essential. Without understanding and sophistication from the public, the commercialization of woven plant fiber laminate components will be a rough threat. Attention on the woven plant fiber laminates must be a collaborative attempt between industrial people, government, and universities. The woven plant fiber laminates have been novel components among scientists for many years; furthermore, people have limited data about these plant fiber laminates. This produces it confronting for industries to utilize woven plant fibers laminates in their brand products. The reason that may be assigned to the user is not to choose the components they are not confident or recognizable. Thus, the industries and government must proceed with the initial process of proposing and advertising woven plant fiber laminates performed by different academic organizations in newspapers and social media. From this method, suitable components produced from woven plant fiber laminates can be conveyed to customers.

8 | CONCLUSIONS

This review describes the development in the field of bio-based polymer nanocomposites. The incorporation of sustainable nanoparticles in eco-friendly resins is essential to achieve higher performance and sustainable nanolaminates. The characteristics of bio-based nanolaminates are based on the crystallinity, interaction between the matrix and fiber, type of nanoparticle, morphology, and behavior of the polymer matrix. The technical advancement of bio-based polymer composites has been examined for biosensors, nanogenerators, automotive parts, electronic packaging, tissue engineering, energy devices, drug delivery, LED, photovoltaics, and supercapacitor applications. In comparison, the woven plant fiber laminates for higher-end application can be produced by coordinating the aspect of the woven fibers. The kinds of yarn and their arrangement in the woven fiber affect the mechanical and physical characteristics of the resulting woven laminate. There are many prospects for fabricating woven laminates, consisting of matrix kinds, fabrication methods, woven fiber attributes, and yarn types. Necessarily, it is critical to investigate the linear density, twist effect, the structure of yarns, mechanical characteristics, and weights because these parameters measure the scheme of the woven fiber.

Many review investigations considered the machining of fiber-based polymer laminates in different prospects, but limited information is present for machining plant fiber laminates. This review also explored recent studies concentrated on traditional and non-traditional machining methods of plant fibers reinforced polymer laminates. It is believed that this review will be beneficial for researchers or scientists or academicians, or any other industrial people seeking expressions in the selection of bio-based fiber, type of matrix, interface bonding between the filler and matrix with the effect of cutting factors, tool geometry and material for the different machining of the plant fiber-reinforced polymer composites.

ACKNOWLEDGMENT

This research was funded by King Mongkut's University of Technology North Bangkok, Thailand with Contract no. KMUTNB-65-KNOW-03.

ORCID

Hemath Mohit https://orcid.org/0000-0003-3618-2558
Sanjay Mavinkere Rangappa https://orcid.org/0000-0001-8745-9532
Suchart Siengchin https://orcid.org/0000-0002-6635-5686
Anish Khan https://orcid.org/0000-0002-3806-5956
Mrityunjay Doddamani https://orcid.org/0000-0002-5537-9404

REFERENCES

[1] R. A. Ilyas, S. M. Sapuan, M. R. M. Asyraf, M. S. N. Atikah, R. Ibrahim, T. T. Dele-Afolabi, M. D. Hazrol, *Biofiller-Reinforced Biodegradable Polymer Composites*, CRC Press, Boca Raton, FL **2020**.

[2] P. Madhu, M. R. Sanjay, M. Jawaid, S. Siengchin, A. Khan, C. I. Pruncu, *Polym. Test.* **2020**, *85*, 106437.

[3] N. H. Sari, C. I. Pruncu, S. M. Sapuan, R. A. Ilyas, A. D. Catur, S. Suteja, Y. A. Sutaryono, G. Pullen, *Polym. Test.* **2020**, *91*, 106751.

[4] S. M. Sapuan, H. S. Aulia, R. A. Ilyas, A. Atiqah, T. T. Dele-Afolabi, M. N. Nurazzi, A. B. M. Supian, M. S. N. Atikah, *Polymer* **2020**, *12*, 2211.

[5] H. Mohit, V. A. M. Selvan, *Compos. Interf.* **2018**, *25*(5–7), 629.

[6] R. A. Ilyas, S. M. Sapuan, *Curr. Org. Synth.* **2020**, *16*, 1068.

[7] R. A. Ilyas, S. M. Sapuan, *Curr. Anal. Chem.* **2020**, *16*, 500.

[8] M. Ramesh, C. Deepa, L. R. Kumar, M. R. Sanjay, S. Siengchin, *J. Ind. Tex.* **2020**, 1. https://doi.org/10.1177/1528083720924730.

[9] A. Shaw, S. Sriramula, P. D. Gosling, M. K. Chryssanthopoulos, *Compos. Part B Eng.* **2010**, *41*, 446.

[10] S. Dinesh, P. Kumaran, S. Mohanamurugan, R. Vijay, D. L. Singaravelu, A. Vinod, M. R. Sanjay, S. Siengchin, K. S. Bhat, *J. Polym. Res.* **2020**, *27*(1), 1.

[11] M. R. M. Asyraf, M. R. Ishak, S. M. Sapuan, N. Yidris, R. A. Ilyas, M. Rafidah, M. R. Razman, *Int. J. Polym. Sci.* **2020**, *2020*, 8878300.

[12] A. Verma, A. Parashar, N. Jain, V. K. Singh, S. M. Rangappa, S. Siengchin, *Biofibers Biopolym Biocompos* **2020**, 1.

[13] T. T. Dele-afolabi, M. A. A. Hanim, R. Calin, R. A. Ilyas, *Microelectron. Reliab.* **2020**, *110*, 113681.

[14] H. Mohit, H. B. Vishwanath, G. H. Kumar, V. A. M. Selvan, M. R. Sanjay, S. Siengchin, *Applications and Drawbacks of Bamboo Fiber Composites, in Bamboo Fiber Composites*, Vol. 247, Springer, Singapore **2021**.

[15] N. Ilie, R. Hickel, *Dent. Mater.* **2009**, *25*, 810.

[16] M. Puttegowda, Y. G. T. Girijappa, S. M. Rangappa, J. Parameswaranpillai, S. Siengchin, S., *Process Eng* **2020**, 17.

[17] M. S. N. Atikah, R. A. Ilyas, S. M. Sapuan, M. R. Ishak, E. S. Zainudin, R. Ibrahim, A. Atiqah, M. N. M. Ansari, R. Jumaidin, *Polimery* **2019**, *64*, 680.

[18] H. Mohit, M. R. Sanjay, S. Siengchin, G. H. Kumar, V. A. M. Selvan, R. Ruban, *Polymer Coatings*, CRC Press, **2020**, 325.

[19] M. R. Sanjay, S. Siengchin, *J. Appl. Agri. Sci. Technol.* **2019**, *31*, 178.

[20] R. Syafiq, S. M. Sapuan, M. Y. M. Zuhri, R. A. Ilyas, A. Nazrin, S. F. K. Sherwani, A. Khalina, *Polymer* **2020**, *12*, 2403.

[21] E. Syafri, M. Sudirman, E. Y. Mashadi, M. Deswita, H. Asrofi, S. M. Abral, R. A. Sapuan, A. F. Ilyas, *J. Mater. Res. Technol.* **2019**, *8*, 6223.

[22] G. R. Arpitha, M. R. Sanjay, P. Senthamaraikannan, C. Barile, B. Yogesha, *Exp. Tech.* **2017**, *41*(6), 577.

[23] D. Athith, M. R. Sanjay, T. G. Y. Gowda, P. Madhu, G. R. Arpitha, B. Yogesha, M. A. Omri, *J. Ind. Tex.* **2018**, *48*(4), 713.

[24] H. Abral, A. Atmajaya, M. Mahardika, F. Hafizulhaq, D. Kadriadi, S. M. Handayani, R. A. Sapuan, *J. Mater. Res. Technol.* **2020**, *9*, 2477.

[25] A. Nazrin, S. M. Sapuan, M. Y. M. Zuhri, R. A. Ilyas, R. Syafiq, S. F. K. Sherwani, *Front. Chem.* **2020**, *8*, 1.

[26] G. R. Arpitha, M. R. Sanjay, B. Yogesha, *Coll. Surf. Sci.* **2017**, *2*(2), 59.

[27] F. A. Sabaruddin, P. M. Tahir, S. M. Sapuan, R. A. Ilyas, S. H. Lee, K. Abdan, N. Mazlan, A. S. M. Roseley, H. P. S. Khalil, *Polymer* **2021**, *13*, 116.

[28] A. Verma, K. Joshi, A. Gaur, V. K. Singh, *J. Mech. Behav. Mater.* **2018**, *27*(5–6), 1.

[29] A. A. B. Omran, A. A. B. A. Mohammed, S. M. Sapuan, R. A. Ilyas, M. R. M. Asyraf, S. S. R. Koloor, M. Petru, *Polymer* **2021**, *13*, 231.

[30] H. Mohit, V. A. M. Selvan, *Fibers Polym.* **2019**, 20, 1918.

[31] D. Liu, A. McDaid, K. Aw, S. Q. Xie, *Mechatronics* **2011**, *21*, 315.

[32] N. Jain, A. Verma, V. K. Singh, *Mater. Res. Exp.* **2019**, *6*, 105373.

[33] N. S. Sharip, T. A. T. Yasim-Anuar, M. N. F. Norrrahim, N. S. Sharip, S. S. Shazleen, N. M. Nurazzi, S. M. Sapuan, R. A. Ilyas, in *Composites in Biomedical Applications* (Eds: S. M. Sapuan, Y. Nukman, N. A. A. Osman, R. A. Ilyas), CRC Press, Boca Raton, FL **2020**, p. 162.

[34] H. Mohit, V. A. M. Selvan, *Indian J. Fiber. Tex. Res.* **2019**, *44*(3), 286.

[35] H. A. Aisyah, M. T. Paridah, S. M. Sapuan, A. Khalina, R. A. Ilyas, N. M. Nurazzi, in *Composites in Biomedical Applications* (Eds: S. M. Sapuan, Y. Nukman, N. A. A. Osman, R. A. Ilyas), CRC Press, Boca Raton, FL **2020**, p. 31.

[36] N. M. Arshad, H. Mohit, M. R. Sanjay, S. Siengchin, A. Khan, M. M. Alotaeibi, A. M. Asiri, M. A. Rub, *Cellulose* **2021**, *28*, 3451.

[37] R. H. Morris, N. R. Geraldi, J. L. Stafford, A. Spicer, J. Hall, C. Bradley, M. J. Newton, *Materials* **2020**, *13*, 1684.

[38] H. Mohit, V. A. M. Selvan, *Int. Polym. Process.* **2020**, *35*(2), 211.

[39] K. Hariprasad, K. Ravichandran, V. Jayaseelan, T. Muthuramalingam, *J. Mater. Res. Technol.* **2020**, *9*, 14029.

[40] R. A. Ilyas, S. M. Sapuan, M. N. Norizan, M. S. N. Atikah, M. R. M. Huzaifah, A. M. Radzi, M. R. Ishak, E. S. Zainudin, S. Izwan, A. M. N. Azammi, *Proceedings of the Prosiding Seminar Enau Kebangsaan*, Vol. 2, Bahau, Malaysia **2019**.

[41] M. L. Sanyang, R. A. Ilyas, S. M. Sapuan, R. Jumaidin, in *Bionanocomposites for Packaging Applications* (Eds: M. Jawaid, S. Swain), Springer, Cham, Switzerland **2018**, p. 125.

[42] N. Mazani, S. M. Sapuan, M. L. Sanyang, A. Atiqah, R. A. Ilyas, in *Lignocellulose for Future Bioeconomy* (Eds: H. Ariffin, S. M. Sapuan, M. A. Hassan), Elsevier, Amsterdam, The Netherlands **2019**, p. 315.

[43] R. Yahaya, S. M. Sapuan, M. Jawaid, Z. Leman, E. S. Zainudin, *Meas. J. Int. Meas. Confed.* **2016**, *77*, 335.

[44] S. N. Monteiro, J. W. Drelich, H. A. C. Lopera, L. F. C. Nascimento, F. S. da Luz, L. C. da Silva, J. L. dos Santos, F. da Costa Garcia Filho, F. S. de Assis, E. P. Lima, *Minerals, Metals and Materials Series; Springer: Berlin/Heidelberg*, Germany **2019**, p. 33.

[45] A. C. Pereira, F. S. De Assis, F. D. C. G. Filho, M. S. Oliveira, L. C. D. C. Demosthenes, H. A. C. Lopera, S. N. Monteiro, *J. Mater. Res. Technol.* **2019**, *8*, 4221.

[46] A. Verma, A. Gaur, V. Singh, *Mater. Perform. Charact.* **2017**, *6*(1), 500.

[47] O. Faruk, A. K. Bledzki, H. P. Fink, M. Sain, *Macromol. Mater. Eng.* **2014**, *299*, 9.

[48] H. Mohit, M. R. Sanjay, S. Siengchin, A. Khan, H. M. Marwani, H. Dzudzevic-Cancar, A. M. Asiri, *J. Polym. Environ.* **2021**, *29*, 2609.

[49] P. K. Bajpai, I. Singh, J. Madaan, *J. Thermoplast. Compos. Mater.* **2014**, *27*, 52.

[50] H. Mohit, R. Srisuk, M. R. Sanjay, S. Siengchin, A. Khan, H. M. Marwani, H. Dzudzevic-Cancar, A. M. Asiri, *J. Polym. Environ.* **2021**, 1.
[51] A. Verma, C. Singh, V. K. Singh, N. Jain, *J. Compos. Mater.* **2019**, *53*(18), 2481.
[52] M. R. Mansor, M. T. Mastura, S. M. Sapuan, A. Z. Zainuddin, *Durability and life prediction in biocomposites, fiber-reinforced composites and hybrid composites*, Elsevier, Amsterdam **2019**, p. 257.
[53] M. R. Sanjay, P. Jyotishkumar, H. K. Mohit, S. Siengchin, *Wood Polymer Composites: Recent Advancements and Applications*, Springer, Singapore **2021**.
[54] P. Ramesh, H. Mohit, V. A. M. Selvan, in *Biobased composites: Processing, Characterization, Properties and Applications* (Eds: A. Khan, S. M. Rangappa, S. Siengchin, A. M. Asiri), Wiley, **2021**, p. 213.
[55] Lucintel, Growth Opportunities in the Global Natural Fiber Composites Market, Lucintel report, 2015.
[56] K. L. Pickering, M. G. A. Efendy, T. M. Le, *Compos. Part A Appl. Sci. Manuf.* **2016**, *83*, 98.
[57] M. R. Sanjay, S. Siengchin, H. N. Dhakal, *Appl. Sci. Eng. Prog.* **2020**, *13*, 183.
[58] K. N. Bharath, P. Madhu, T. G. Y. Gowda, A. Verma, M. R. Sanjay, S. Siengchin, *Polym. Compos.* **2020**, *41*(11), 4550.
[59] C. Elanchezhian, B. V. Ramnath, G. Ramakrishnan, M. Rajendrakumar, V. Naveenkumar, M. K. Saravanakumar, *Mater. Today Proc.* **2018**, *5*, 1785.
[60] D. Chandramohan, A. J. Presin Kumar, *Data Brief.* **2017**, *13*, 460.
[61] E. Omrani, P. L. Menezes, P. K. Rohatgi, *Eng. Sci. Technol.* **2016**, *19*, 717.
[62] A. Verma, L. Budiyal, M. R. Sanjay, S. Siengchin, *Polym. Eng. Sci.* **2019**, *59*(10), 2041.
[63] M. K. Marichelvam, P. Manimaran, A. Verma, M. R. Sanjay, S. Siengchin, K. Kandakodeeswaran, M. Geetha, *Polym. Compos.* **2021**, *42*, 512.
[64] N. Amir, K. A. Z. Abidin, F. B. M. Shiri, *Procedia. Eng.* **2017**, *184*, 573.
[65] M. Rajesh, J. Pitchaimani, N. Rajini, *Procedia Eng.* **2016**, *144*, 1055.
[66] E. Jayamani, S. Hamdan, M. R. Rahman, M. K. B. Bakri, *Procedia Eng.* **2014**, *97*, 545.
[67] R. D. Anandjiwala, S. Blouw, *J. Nat. Fiber.* **2007**, *4*(2), 91.
[68] W. Brostow, H. E. H. Lobland, *Materials: Introduction and Applications*, Wiley, New Jersey **2016**.
[69] H. Mohit, V. A. M. Selvan, *Matter: Int. J. Sci. Technol.* **2019**, *4*(3), 157.
[70] U. Kusebauch, S. A. Cadamuro, H. J. Musiol, L. Moroder, C. Renner, *Chem. – Eur. J.* **2007**, *13*, 2966.
[71] M. Hemath, J. Tengsuthiwat, S. M. Rangappa, S. Siengchin, A. Khan, H. M. Marwani, H. Dzudzevic-Cancar, A. M. Asiri, *Polym. Compos.* **2021**, 1.
[72] A. A. de Souza Machado, W. Kloas, C. Zarfl, H. Hempel, M. C. Rilling, *Global Change. Biol.* **2018**, *24*, 1405.
[73] D. Braun, *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 578.
[74] V. K. Thakur, M. K. Thakur, M. R. Kessler, *Handbook of Composites from Renewable Materials, Biodegradable Materials*, Vol. 5, Wiley, **2017**.
[75] V. K. Thakur, M. K. Thakur, P. Raghavan, M. P. Kessler, A. C. S. Sustain, *Chem. Eng.* **2014**, *2*, 1072.
[76] L. Shen, E. Worrell, M. Patel, *Biofuel Bioproduct. Biorefin.* **2010**, *4*, 25.
[77] R. Vendamme, N. Schüwer, W. Eevers, *J. Appl. Polym. Sci.* **2014**, *131*(17), 1.
[78] J. Zhang, G. Chen, G. S. Bhat, H. Azari, H. Pen, *J. Appl. Polym. Sci.* **2020**, *137*, 48309.
[79] T. Wei, L. Lei, H. Kang, B. Qiao, Z. Wang, L. Zhang, P. Coates, K. C. Hua, J. Kulig, *Adv. Eng. Mater.* **2012**, *14*, 112.
[80] D. Kalita, A. N. Netravali, *Tex. Fin.* **2017**, 425.
[81] B. Nutan, A. K. S. Chandel, S. K. Jewrajka, *Chem. Eur. J.* **2017**, *23*, 8166.
[82] A. Llevot, P. K. Dannecker, M. von Czapiewski, L. C. Over, Z. Soyler, M. A. R. Meier, *Chem. Eur. J.* **2016**, *22*, 11510.
[83] T. Tsujimoto, H. Uyama, S. Kobayashi, *Macromol. Rap. Commun.* **2003**, *24*, 711.
[84] D. Akram, S. Ahmad, E. Sharmin, S. Ahmad, *Macromolecul. Chem. Phys.* **2010**, *211*, 412.
[85] A. Kausar, *Mater. Res. Innovations* **2020**, 1.
[86] M. Du, B. Guo, D. Jia, *Polym. Int.* **2010**, *59*, 574.
[87] G. Cavallaro, G. Lazzara, S. Milioto, F. Parisi, *J. Therm. Anal. Calor.* **2014**, *117*, 1293.
[88] J. Praveenkumara, P. Madhu, T. G. Y. Gowda, M. R. Sanjay, S. Siengchin, *J. Tex. Inst.* **2021**, 1. https://doi.org/10.1080/00405000.2021.1920151.
[89] M. Wang, S. Li, Y. Zhang, J. Huang, *Chem. – Eur. J.* **2015**, *21*, 16195.
[90] T. Baran, N. Y. Baran, A. Menteş, *Appl. Organomet. Chem.* **2018**, *32*, 4075.
[91] L. Jong, *J. Appl. Polym. Sci.* **2013**, *130*, 2188.
[92] L. Zhang, W. Liu, W. Shi, X. Xu, J. Mao, P. Li, C. Ye, R. Yin, S. Ye, X. Liu, X. Cao, C. Gao, *Chem. – Eur. J.* **2018**, *24*, 13792.
[93] J. Ding, O. U. Rahman, Q. Wang, W. Peng, H. Yu, A. C. S. Sustain, *Chem. Eng.* **2017**, *5*, 7792.
[94] A. Verma, K. Baurai, M. R. Sanjay, S. Siengchin, *Polym. Compos.* **2020**, *41*(1), 338.
[95] L. W. Fan, X. Fang, X. Wang, Y. Zeng, Y. Xiao, Z. Yu, X. Xu, Y. Hu, K. Cen, *Appl. Energ.* **2013**, *110*, 163.
[96] P. Costa, J. Nunes-Pereira, J. Oliveira, J. Silva, J. A. Moreira, S. A. C. Carabineiro, J. G. Buijnsters, S. Lanceros-Mendez, *Compos. Sci. Technol.* **2017**, *153*, 241.
[97] Y. Fang, X. Du, Y. Jiang, Z. Du, P. Pan, X. Cheng, H. Wang, A. C. S. Sustain, *Chem. Eng.* **2018**, *6*, 14490.
[98] I. R. S. Vieira, G. D. S. Miranda, E. Ricci-Júnior, M. C. Delpech, *e-Polym.* **2019**, *19*, 168.
[99] W. Fang, L. Liu, G. Guo, *Chem. – Eur. J.* **2017**, *23*, 11253.
[100] O. I. H. Dimitry, Z. Abdeen, E. A. Ismail, L. G. Saad, *Int. J. Green Nanotechnol.* **2011**, *3*, 197.
[101] A. Ambrosi, M. Pumera, *Chem. Eur. J.* **2016**, *22*, 153.
[102] I. R. S. Vieira, L. D. F. De Oliveira Costa, G. dos Santos Miranda, S. Nardecchia, M. S. S. B. Monteiro, E. Ricchi-Juinor, M. Delpech, *J. Polym. Environ.* **2020**, *28*, 74.
[103] M. A. Morsi, A. H. Oraby, A. G. Elshahawy, R. M. El-Hady, *J. Mater. Res. Technol.* **2019**, *8*, 5996.
[104] P. Alexandridis, *Chem. Eng. Technol.* **2011**, *34*, 15.
[105] R. Kumar, B. Rai, G. Kumar, *J. Polym. Environ.* **2019**, *27*, 2963.

[106] B. W. Chieng, N. A. Ibrahim, W. M. Z. Wan Yunus, M. Z. Hussein, V. S. G. Silverajah, *Int. J. Mol. Sci.* **2012**, *13*, 10920.
[107] S. A. McGlashan, P. J. Halley, *Polym. Int.* **2003**, *52*, 1767.
[108] X. Cao, Y. Chen, P. R. Chang, M. Stumborg, M. A. Huneault, *J. Appl. Polym. Sci.* **2008**, *109*, 3804.
[109] D. Klemm, F. Kramer, S. Moritz, T. Lindstrom, M. Ankerfos, D. Gray, A. Dorris, *Angew. Chem., Int. Ed.* **2011**, *50*, 5438.
[110] H. Kang, K. Zuo, Z. Wang, L. Zhang, L. Liu, B. Guo, *Compos. Sci. Technol.* **2014**, *92*, 1.
[111] R. A. Ilyas, S. M. Sapuan, M. S. N. Atikah, M. R. M. Asyraf, S. A. Rafiqah, H. A. Aisyah, N. M. Nurazzi, M. N. F. Norrrahim, *Text. Res. J.* **2021**, *91*, 152.
[112] R. Sepe, F. Bollino, L. Boccarusso, F. Caputo, *Compos. Part B Eng.* **2018**, *133*, 210.
[113] W. Jordan, P. Chester, *Procedia Eng.* **2017**, *200*, 283.
[114] H. Abral, J. Ariksa, M. Mahardika, D. Handayani, I. Aminah, N. Sandrawati, A. B. Pratama, N. Fajri, S. M. Sapuan, R. A. Ilyas, *Food Hydrocolloids* **2020**, *98*, 105266.
[115] K. N. Bharath, P. Madhu, T. G. Y. Gowda, A. Verma, M. R. Sanjay, S. Siengchin, *Mater. Perform. Charact.* **2021**, *10*(1), 99.
[116] H. M. Kavya, S. Bavan, M. R. Sanjay, S. Siengchin, S. Gorbatyuk, *Polym. Compos.* **2021**, *42*(8), 3911.
[117] M. Hemath, V. A. M. Selvan, *Polym. Compos.* **2020**, *41*(5), 1878.
[118] M. Hemath, S. M. Rangappa, V. Kushvaha, H. N. Dhakal, S. Siengchin, *Polym. Compos.* **2020**, *41*(10), 3940.
[119] P. Kumaran, S. Mohanamurugan, P. Madhu, R. Vijay, D. L. Singaravelu, A. Vinod, M. R. Sanjay, S. Siengchin, *J. Ind. Tex.* **2020**, *50*(4), 427.
[120] A. Vinod, R. Vijay, D. L. Singaravelu, M. R. Sanjay, S. Siengchin, M. M. Moure, *Mater. Res. Exp.* **2019**, *6*(8), 085406.
[121] M. Arulmurugan, A. S. Selvakumar, K. Prabu, G. Rajamurugan, *Bull. Mater. Sci.* **2020**, *43*, 58.
[122] P. Madhu, M. R. Sanjay, A. Khan, A. Al Otaibi, S. A. Al-Zahrani, S. Pradeep, B. Yogesha, *J. Nat. Fibers.* **2020**, *1*, 1.
[123] H. Awais, Y. Nawab, A. Amjad, A. Anjang, H. M. Akil, M. S. Z. Abidin, *Compos. Part B Eng.* **2019**, *177*, 107279.
[124] U. Kureemun, M. Ravandi, L. Q. N. Tran, W. S. Teo, T. E. Tay, H. P. Lee, *Compos. Part B Eng.* **2018**, *134*, 28.
[125] J. Torres, L. Vandi, M. Veidt, M. T. Heitzmann, *Compos. Part A Appl. Sci. Manuf.* **2017**, *98*, 99.
[126] T. B. Yallew, E. Kassegn, S. Aregawi, A. Gebresias, *SN Appl. Sci.* **2020**, *2*, 338.
[127] D. Sivakumar, L. F. Ng, S. M. Lau, K. T. Lim, *J. Polym. Environ.* **2018**, *26*, 499.
[128] N. Ayrilmis, S. Jarusombuti, V. Fueangvivat, P. Bauchongkol, R. H. White, *Fibers. Polym.* **2011**, *12*(7), 919.
[129] M. D. H. Beg, S. Samahani, M. F. Mina, R. M. Yunus, *J. Reinf. Plast. Compos.* **2013**, *32*(17), 1268.
[130] K. N. Bharath, S. Basavarajappa, *Proc. Mater. Sci.* **1880**, *2014*, 5.
[131] A. M. Redwan, *Chem. Res. J.* **2020**, *5*(6), 247.
[132] I. Shyha, S. L. Soo, D. Aspinwall, S. Bradley, *J. Mater. Process. Technol.* **2010**, *210*, 1023.
[133] R. Teti, C. I. R. P. Ann, *Manuf. Technol.* **2002**, *51*, 611.
[134] K. Patel, P. Gohil, V. Chaudhary, *Appl. Mech. Mater.* **2018**, *877*, 177.
[135] E. Uhlmann, S. Richarz, F. Sammler, R. Hufschmied, *Procedia. Manuf.* **2016**, *6*, 113.
[136] N. Bhatnagar, N. K. Naik, N. Ramakrishnan, *Mater. Manuf. Processes* **1993**, *8*, 683.
[137] J. P. Davim, F. Mata, V. N. Gaitonde, S. R. Karnik, *J. Thermoplast. Compos. Mater.* **2010**, *23*, 5.
[138] K. Balasubramanian, M. T. H. Sultan, F. Cardona, N. Rajeswari, *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *152*, 1.
[139] P. J. Herrera-Franco, A. Valadez-Gonzalez, *Compos. Part A Appl. Sci. Manuf.* **2004**, *35*, 339.
[140] R. Jeyapragash, V. Srinivasan, S. Sathiyamurthy, *Mater. Today: Proc.* **2020**, *22*, 1223.
[141] A. Lotfi, H. Li, D. V. Dao, G. Prusty, *J. Thermoplast. Compos. Mater.* **2021**, 1.
[142] M. Nurhaniza, M. K. A. M. Ariffin, F. Mustapha, B. T. H. T. Baharudin, *Int. J. Manuf. Eng.* **2016**, *2016*, 1.
[143] J. O'Hara, F. Fang, *Int. J. Extreme Manuf.* **2019**, *1*, 032003.
[144] J. Haider, M. S. J. Hashmi, *Health and Environmental Impacts in Metal Machining Processes*, Elsevier, Amsterdam **2014**.
[145] T. S. Srivatsan, C. T. Lane, D. M. Bowden, *Mach. Compos. Mater.* **1994**, *II*, 85.
[146] A. Caggiano, *Materials* **2018**, *11*, 1.
[147] S. D. Kumar, J. Ghose, A. Mandal, *Thixoforming of Lightweight Alloys and Composites: an Approach Toward Sustainable Manufacturing*, Elsevier, Amsterdam **2019**.
[148] P. J. Pawar, U. S. Vidhate, M. Y. Khalkar, *J. Comput. Des. Eng.* **2018**, *5*, 319.
[149] A. Dhanawade, S. Kumar, R. V. Kalmekar, *Def. Sci. J.* **2014**, *66*, 522.
[150] B. Bhattacharyya, B. Doloi, *Mod. Machin. Technol.* **2020**, 21.
[151] M. C. P. Selvan, N. M. S. Raju, *Front. Mech. Eng.* **2012**, *1*, 929.
[152] S. Vigneshwaran, M. Uthayakumar, V. Arumugaprabu, *J. Reinf. Plast. Compos.* **2018**, *37*, 230.
[153] G. Chryssolouris, K. Salonitis, *Mach. Technol. Compos. Mater.* **2012**, 266.
[154] J. D. Majumdar, I. Manna, Sadhana, *Acad. Proc. Eng. Sci.* **2003**, *28*, 495.
[155] G. D. Gautam, A. K. Pandey, *Opt. Laser. Technol.* **2018**, *100*, 183.
[156] G. Chryssolouris, P. Stavropoulos, K. Salonitis, in *Handbook of Manufacturing Engineering and Technology* (Ed: A. Nee), Springer, London **2013**, p. 1.
[157] S. O. Ismail, S. O. Ojo, H. N. Dhakal, *Compos. Part B Eng.* **2017**, *108*, 45.
[158] J. L. Merino-Perez, R. Royer, E. Merson, A. Lockwood, S. Ayvar-Soberanis, M. B. Marshall, *Compos. Struct.* **2016**, *140*, 621.
[159] S. O. Ismail, H. N. Dhakal, E. Dimla, I. Popov, *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2017**, *231*, 2527.
[160] K. K. Panchagnula, K. Palaniyandi, *J. Mater. Res. Technol.* **2018**, *7*, 180.
[161] J. E. Ribeiro, M. B. Cesar, H. Lopes, *Procedia. Struct. Integr.* **2017**, *5*, 355.
[162] J. P. Davim, P. Reis, *J. Mater. Process. Technol.* **2005**, *160*, 160.
[163] F. Chegdani, S. Mezghani, M. E. Mansori, *Surf. Coatings. Technol.* **2015**, *284*, 264.
[164] M. Zurayyen, A. Mutalib, M. J. Jamal, *J. Eng. Sci. Res.* **2017**, *1*, 9.

[165] R. Voss, L. Seeholzer, F. Kuster, K. Wegener, *CIRP J. Manuf. Sci. Technol.* **2017**, *18*, 75.
[166] J. A. Ghani, L. A. Choudhury, H. H. Hassan, *J. Mater. Process. Technol.* **2004**, *145*, 84.
[167] M. Puttegowda, S. M. Rangappa, A. Khan, S. A. Al-Zahrani, A. Al Otaibi, P. Shivana, M. M. Moure, S. Siengchin, *Polym. Compos.* **2020**, *41*(11), 4572.
[168] R. Arun Ramnath, P. R. Thyla, N. M. Kumar, S. Aravind, *J. Reinf. Plast. Compos.* **2018**, *37*, 77.
[169] J. Zajac, Z. Hutyrova, I. Orlovsky, *Adv. Mater. Res.* **2014**, *941–944*, 275.
[170] G. Sivakiran, Y. Gangwal, G. Venkatachalam, C. Pandivelan, S. Ayyappan, *Mater. Today Proc.* **2018**, *5*, 7908.
[171] H. A. Aisyah, M. T. Paridah, A. Khalina, S. M. Sapuan, M. S. Wahab, O. B. Berkalp, C. H. Lee, S. H. Lee, *Polymer* **2018**, *10*, 1320.
[172] V. K. Balla, K. H. Kate, J. Satyavolu, P. Singh, J. G. D. Tadimeti, *Compos. Part B Eng.* **2019**, *174*, 106956.
[173] A. Le Duigou, D. Correa, M. Ueda, R. Matsuzaki, M. Castro, *Mater. Des.* **2020**, *194*, 108911.
[174] D. A. Kumar, G. G. Raj, G. Shivaani, V. M. Sreehari, *Int. J. Mech. Eng. Technol.* **2018**, *9*, 1262.
[175] C. H. Lee, M. S. Salit, M. R. Hassan, *Adv. Mater. Sci. Eng.* **2014**, *2014*, 514036.

How to cite this article: H. Mohit, S. Mavinkere Rangappa, S. Siengchin, S. Gorbatyuk, P. Manimaran, C. Alka Kumari, A. Khan, M. Doddamani, *Polym. Compos.* **2022**, *43*(1), 608. https://doi.org/10.1002/pc.26403