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Banana Fibrere In Forced Polymer Composites-Ashort Review

[1]Chethan H M, [2]Abhishek M, [3]Akash C P, [4]Darshan H E, [5]Ashrith H S
[12345] Department of Mechanical Engineering, Malnad Collegeof Engineering, Hassan ,India

Abstract:Bananafibre(BNF),obtainedfromthepseudostemofthebananaplant,isattracting interest as a reinforcement material in polymer composites owing to its abundance, low cost, and eco-friendly nature. This review explores the latest developments in BNF-reinforced polymer composites (BFRPCs), focusing on their production, properties, and uses. It covers aspects like the fibres chemical makeup and surface treatments used to improvebonding with different types of polymers, including both thermoplastics and thermosets. The article also examines into the composite's mechanical strength, heat resistance, and biodegradability, as well as the methods used to manufacture them. This comprehensive analysis underscores the significant potential of BFRPCs as eco-friendly alternatives to synthetic composites in advancing a circular economy and sustainable development

Index Terms - Natural Fibres; Polymer Composites; Sustainable Materials; Mechanical Properties

I. Introduction

Choosingtherightmaterialfordesigningandmanufacturingasustainableproductiscrucialin engineering applications. It is important to analyse the material's physical and mechanical properties to create a product that meets customer satisfaction. Among different materials, composites offer advantages in terms of processing ease, increased productivity, and cost reduction. Composites are customizable materials, allowing their properties to be adjusted by modifying the matrix and reinforcement phases. The matrix can be made from polymers, metals, or ceramics, while there enforcement an take whiskers, particles, fibres, or structural elements forms. Composite materials are increasingly being used to replace traditional materials. With the fast-paced advancement of industrial technologies, the development of innovative material designs has become crucial. Among these, polymer composites are gaining recognition as a better alternative owing to their lightweight nature, high strength, and cost-effectiveness [1].

Recent technological advancements have increased the demand for advanced materials in critical areas such as spacecraft, aerodynamics, missile technology, and automobiles. Composite materials are considered ideal for these applications as they can be customized to meetspecificstrengthrequirementsbasedontheenduser'sneeds.Tomeetthediversematerial demands of modern industries, researchers have been experimenting with various combinations of fibres and matrix materials to develop stronger, more efficient materials for differentindustrialsectors[2,3].Inrecenttimes,theriseoftechnologyhasencouragedtheuse of environmentally friendly resources, especially plant-based ones, considering ecological impact and renewability. As a result, natural fibre composites (NFCs) have drawn significant interest for their sustainable and eco-conscious benefits. But not all naturally occurring plants are suitable for composite reinforcement; ideal fibres should bee as to extract, bond well with the matrix, and contain appropriate levels of cellulose (6–80%)and lignin(5–20%).The need or NFC is growing rapidly in various industries due to their potential environmental, economic, and performance benefits. These materials are created by blending natural fibres like flax, hemp, jute, or sisal with a binding substance typically, a polymer resin, to form a composite material [4, 5].

Tropical countries such as India have an abundance offibrous plants,with banana standingout as one of the key agricultural crops. At present, banana fibre (BNF) is often regarded as by product of banana farming; however, it can be repurposed for industrial applications without incurring extra expenses. In India, which contributes 27% of the world's banana production, BNFisalow-costbyproductofcultivation.Outofaround300bananaplantspecies,only about 20 are consumed as food. Nearly every part of the banana plant including its leaves, peel, fruit, flower, stalk, and pseudostem can be effectively utilized. The plant finds applications in both food and non-food sectors, such as flavouring agents, colorants, livestock feed, fertilizers, and as a source of bioactive compounds. Banana leaves are commonly utilized in food packaging and preparation in some regions, while the fruit is globally popular for its nutritional value. Its fibres serve purposes intextiles, paper production, and as reinforcement incomposites because oftheirhighcelluloseandlignincontent.Theplantalsooffersmedicinalbenefits;forinstance, the flower is used to treat ailments like ulcers and bronchitis. In recent decades, extensive research has focused on the efficient use of BNF as a reinforcing agent in polymer matrices. As a result, a comprehensive and structured review has been carried out to explore its potential in polymer composite applications [6-9].

II. PROPERTIESOFBNF

BNF extracted from the pseudostem of banana plants primarily from the Musa species is gaining appreciation as a sustainable and robust reinforcement material in composite production. Its unique physical, chemical, mechanical, and thermal properties play a significant roleinenhancingtheoverallperformanceofcomposites[10].Thefollowingisanexamination of these properties and their impact on the performance of composite materials.

2.1PHYSICALPROPERTIES

BNF, which comes from the stalk of the banana plant, is a sustainable and environmentally friendly natural material with distinctive physical properties that make it highly versatile for various applications. Its physical characteristics are governed by factors such as thevariety of the banana plant ,growth conditions,andextractionmethods.BNFisgenerallylightweightyet strong, making it an excellent alternative to synthetic and other natural fibres in terms of sustainability and durability. BNF is made up of cellulose, hemicellulose, and lignin, which together give it strength and flexibility. The fibre exhibits a lustrous appearance, often compared to silk, and its natural golden sheen adds an aesthetic appeal. This characteristic makes it suitable for creating textiles, ropes, mats, and composite materials. The fibre's diameter ranges from 80 to 250 microns, depending on the extraction method and the plant's maturity. Another critical property of BNF is its moisture-absorbing capacity, attributed to its hydrophilic nature. This property ensures that BNF-based products are breathable and comfortable, especially in textiles. However, its high moisture absorption also makes it prone to biodegradation, a factor to consider in certain applications [11, 12].In additiontothese, BNFhasauniquemicrostructurecharacterizedbyfine anduniformcells, contributing to its lightweight and smooth texture. These features enable its use in delicate applications like handicrafts and paper production. Its biodegradability and renewability also underscore its importance in eco-conscious industries, offering a sustainable alternative to synthetic materials. Despite its impressive physical properties, BNF does have limitations, includingitslowerresistancetoprolonged exposuretoultravioletraysanditssusceptibilityto mould in humid conditions. However, these drawbacks are often mitigated through surface treatments and blending with other fibres. Overall, the physical properties of BNF make it an invaluableresourceforsustainableinnovationsinindustriessuchasfashion,construction ,and agriculture. Its density, approximately 1.35 g/cm³, is equivalent to natural fibres like jute and sisal, positioning it as a competitive material in various industries. Furthermore, the fibre's resistance to alkali conditions and moderate resistance to acidic environments enhance its durability in challenging applications [13-15].

2.2 Chemical Properties

BNF, which comes from the pseudo-stem of the banana plant, has a special chemical makeup that gives it useful qualities and allows for a wide range of uses. It mainly contains cellulose, hemicellulose, lignin, and pectin, along with small amounts of waxes, ash, and moisture. Cellulose makes up about 60-65% of the fibre and is responsible foritsstrong tensile strength andrigidity,makingitidealforuseinproductsliketextiles,ropes,andreinforcedcomposites. Hemicellulose,whichmakesuparound15-20%,helpsholdthecellulosemicrofibrilstogether andaffectshowmuchwaterthefibrecanabsorb.Lignin,makingup5-10%ofthefibre,imparts rigidity and contributes to its biodegradability and resistance to microbial degradation, althoughitcanposechallengesduringprocessingduetoitshydrophobicnature.Theexistence of pectin, waxes, and other minor constituents helps maintain the structural integrity of the fibre,facilitatingitsuseinsustainablematerials.Furthermore,BNFexhibitsexcellentmoisture absorption, attributed to its hydrophilic cellulose content, making it comfortable for use in textiles. The fibre's chemical stability and resistance to alkalis enhance its utility in various chemical treatments, dyeing processes, and composite manufacturing [15-19].

However, the high cellulose content also makes BNF prone to degradation under acidic conditionsorprolongedexposuretosunlight,whichcanleadtothebreakdownofitsmolecular structure.ThesepropertieshighlightBNF'spotentialasaneco-friendlyalternativetosynthetic fibres, promoting its application in biodegradable products, green composites, and eco- conscious packaging materials. Understanding the chemical properties of BNF enables advancementsinitsprocessingtechniquesandoptimizationfor diverseindustrialapplications [20].

2.3 MechanicalProperties

BNFs exhibit good tensile strength, typically ranging from 100 to 500 MPa, depending on factors such as fibre type, extraction method, and moisture content. This makes them suitable for high-strength composite applications, where load-bearing performance is critical. The modulusofelasticityofBNFsisrelativelyhigh,intherangeof5–20GPa,contributingtostiffness and rigidity in composites. This property enhances the composite's ability to resist deformationunderload.BNFalsoexhibitsexcellentelongationproperties,rangingbetween3- 10%, making it flexible and resistant to wear [7, 16, 21-23].

2.4 ThermalProperties

BNFhave moderate thermal stability, with decomposition typically occurring at temperatures around250–300°C.Whilethisislowerthansomesyntheticfibreslikeglassorcarbon,itisstill sufficient for many standard applications where the composite is not exposed to extreme temperatures.BNFsarenotexcellentthermalconductorsbutarebetterthansomeothernatural fibres in this regard. In composite form, they help in maintaining low thermal conductivity, which is beneficial for insulation applications, such as in building materials. When used in composites,BNFscanimprovetheheatresistanceoftheoverallmaterialwhencombinedwith therightpolymermatrix(e.g.,thermosettingresins).However,thefibre'sthermalperformance canbeenhancedfurtherbytreatmentprocesseslikecoatingorfibreimpregnation.Thethermal properties of BNF are notable, with it having a low thermal conductivity, which enhances its potential for use in insulation materials [24-26].

III. FabricationandProcessingTechniques

Thedevelopmentofsustainableandeco-friendlymaterialshasattainedsignificantattentionin recent years, driven by growing concerns about environmental degradation and the need for reduced carbon footprints. One promising area of research involves the use of natural fibres, such as BNF, as reinforcement in polymer composites. These composites offer a range of benefits, including biodegradability, renewability, and reduced dependence on synthetic materials.BNFcontainahighamountofcelluloseandwidelyusedtomaketextiles,paper,and other environmentally friendly products. The extraction process varies depending on the methodused,buttheoverviewofacommonandtraditionalapproachtoBNFextractionalong with BFRPC fabrication is discussed in the following sections.

3.1 BNF EXTRACTION

BNFextractionisaprocessofobtainingnaturalfibresfromthepseudo-stemsofbananaplants, which are typically discarded as agricultural waste. The process begins by harvesting the pseudo-stems after the fruiting cycle of the banana plant. The outer layers are removed, and theinnersheath is stripped manually orusing adecorticatormachine.The extractedfibres are then cleaned to remove impurities, dried under sunlight, and combed to separate individual fibres. These fibres are eco-friendly, biodegradable, and widely used in industries such as textiles,paper,andhandicraftsduetotheirstrength,durability,andnaturalsheen.Theprocess is an excellent example of sustainable resource utilization, turning waste into valuable products. BNFs were obtained from the sheaths of banana stems using a fibre extraction machine.Theprocessincludedcrushingthestem,followedbycleaningandcombingthefibres. Afterextraction,thefibresweredriedinahotairovenat100°Cfor4hoursto eliminate moisture [12, 27, 28].

3.2 MANUFACTURINGOF COMPOSITES

Composite manufacturing is a transformative process at the heart of modern engineering, where materialswithdistinctlydifferentpropertiestypicallyahigh-strengthreinforcementlikefibresand a supportive matrix such as resin are combined to create a single, unified material. The reinforcement lends mechanical strength and rigidity, while the matrix binds the structure, distributing loads and protecting the fibres from environmental and mechanical damage. The methods used for fabrication these materials are as varied as the applications they serve each with its own set of advantages. The most prominent techniques are hand lay-up (HL), compression moulding (CM), injection moulding (IM), resin transfer moulding (RTM), and pultrusion. Of these, the HL and CM processes stand as the most widely used approaches, especiallyinthefabricationofhybridcompositeswithspecificstackingsequences.Composite manufacturing is valued for its ability to customize materials to meet specific performance requirements, making it a cornerstone of modern engineering and design [29-31].

Handlay-upprocessstartswithaselectionofsmooth,clean,anddrysurfaceasthefoundation. To facilitate easy removal of the finished composite, a thin coat of mould-release agent, often a silicone-based spray, is evenly applied. This preparation ensures the composite will not adhere to the mould, allowing for a clean, undamaged release once curing is complete. The nextstageisthecarefulpreparationoftheresin-hardenermixture,which is poured and spread evenlyacrossthemouldsurface,formingtheinitialadhesivelayer.Ontothis,thefirstlayerof dry fibre reinforcement is carefully placed. A second coat of resin is applied over the reinforcementandisthoroughlyimpregnatedusingamechanicalroller,ensuringtheresinfully saturates the fibres, eliminating air bubbles and creating a strong fibre-matrix bond. Layer by layer, this sequence is recurring until the desired thickness or layering configuration is obtained.Theselayers,tailoredtomeetspecificstructuraldemands,definethefinalmechanical properties of the composite. Once all layers are in place, a second mould also coated with a release agent is positioned over the stack. A uniform load is then applied, compressing the entire assembly. This pressure not only consolidates the layers but also ensures even resin distributionandminimizesvoidcontent.Thecompressed compositeisthenlefttocure, either at room temperature or with the aid of controlled heating, depending on the resin system used [32-34].

3.3 SurfaceTreatment

TreatingthesurfaceofBNFiscrucialtoimprovingitscompatibilitywithpolymermatricesin compositeproduction. Untreated fibres often have surface impurities, waxes, and hydrophilic properties, which can hinder adhesion with hydrophobic matrix materials. Common surface treatments include alkali treatment (using sodium hydroxide to remove lignin and hemicellulose),silanetreatment(toimprovebondingwithsyntheticresins),andacetylation(to reduce moisture absorption). These treatments modify the fibre's surface, improving its mechanicalproperties,durability,andinterfacialadhesionwiththematrix.[15]Propersurface treatment not only enhances the performance of BNF composites but also expands their applications in industries such as automotive, construction, and packaging. Although BNFs have advantages over synthetic fibres in terms of cost, low density, recyclability, and natural abundance,theyalsohavecertaindrawbacks,includingmoistureabsorption,qualityvariations, thermal instability, and poor wettability. The high moisture absorption is primarily due to the presenceofhemicellulose.Additionally,thehydrophilicnatureoflignocellulosicfibrescontrastswiththehydrophobicnatureofresin,leadingtoweakinterfacialbondingatthefibre- matrix interface. This poor bonding reduces the mechanical properties of NFC [35, 36].

Alkali treatment, also known as alkalization or mercerization, is a widely adopted surface modification method for natural fibres used in composite fabrication. The treatment involves immersingthefibresinasodiumhydroxide(NaOH)solutionundercontrolledtemperatureand time conditions. This chemical process modifies the fibre’s surface morphology and composition, thereby improving compatibility and interfacial bonding with polymer matrices. During thetreatment, non-cellulosicmaterials such aslignin,hemicellulose,waxes,andsurface oils are effectively removed. The breakdown of hydrogen bonds in the crystalline regions causes fibre swelling and introduces new reactive hydrogen bonding sites, which in turn reduces thefibre’s tendency to absorbmoisture.Alkali treatment also leads to asmootherand more uniform fibre surface, minimizing micro-voids and improving mechanical interlocking with the matrix. Additionally, the process often results in a reduction of fibre diameter, which increases the aspect ratio a critical factor in efficient stress transfer across the composite. However,cautionmustbeexercisedtoavoidexcessiveNaOHconcentration,whichcanresult inover-delignificationandweakeningofthefibrestructure. Whenoptimized,alkalitreatment significantly enhances the mechanical, thermal, and moisture resistance properties of natural fibre composites, such as those reinforced with BNFs [37, 38].

IV. MechanicalAndThermalPropertiesofBNFComposites:

BNFcompositesarerecognizedfortheirstrongmechanicalperformance,includingimpressive tensile strength, rigidity, and resistance to wear. These qualities are largely due to the high cellulose content in BNFs, which ranges from about 60% to 65%, and greatly enhances the strength of the composite material. Among these properties, tensile strength is particularly important it measures how well the material can withstand pulling forces without breaking. The addition of BNFs in polymer matrices significantly enhances the tensile strength, making itaviablealternativetosyntheticfibreslikeglassandcarbonincertainapplications.Thefibre's natural reinforcement improves the stiffness of the composite, reducing its deformation under load. Another important mechanical property is the flexural strength, which measures the composite’s ability to withstand bending forces. BFRPCs exhibit favourable flexural strength due to the fibre's high rigidity. The effectiveness of the composite can vary based on the type of polymer matrix and how well the fibres bond with it. Using advanced processing methods, like treating the fibre surfaces with alkaline solutions, can strengthen the bond between fibres andthematrix,whichinturnimprovesthecomposite'smechanical properties.Moreover,BNF composites show good impact resistance. The fibres act as a reinforcement to absorb and dissipate the energy when impacted, which is beneficial for automotive, construction, and packaging applications. However, the impact resistance of BFRPCs can vary depending on factors like fibre length, fibre orientation, and the type of polymer matrix.

The BFRPCs thermal characteristics, such as thermal stability, heat resistance, and thermal conductivity, are essential for their use in applications involving high temperatures or fluctuating thermal environments. BNF itself has a relatively low thermal conductivity due to the high cellulose content, which imparts a certain degree of thermal insulation. However, the composite'soverallthermalperformanceisinfluencedbythetypeofpolymermatrixandthefibrecontentratio. BNF composites show moderate to good thermal stability, with their decomposition temperature typically ranging from 200 to 250°C. The polymer matrix can affect the thermal degradation of the composite, with some matrices offering higher thermal stability than others. For example, when combined with thermosetting resins like epoxy or polyester, BNF composites show better resistance to heat and less thermal degradation than when combined with thermoplastic resins. One significant advantage of BFRPCs is their biodegradability and reduced environmental impact, especially in comparison to synthetic materials that can release harmful gases during high-temperature degradation. With the growing demand for sustainable materials, the thermal properties of BFRPCs make them a viable option for green building materials, automotive components, and other applications requiring temperatureresistance. Recent research articles discussed below has comprehensively examined a variety of BFRPCs, emphasizing advancements in fabrication techniques, surface modifications, and performance evaluations to enhance their mechanical, thermal, and environmental properties.

Balaji et al. [5] evaluated BNF-reinforced epoxy composites, examining the effects of fibre weight percentage and length on their mechanical, thermal, and morphological properties. In the study composites were fabricated with fibre loadings ranging from 5% to 20% and fibre lengthsof10mmand20mmusingacompressionmouldingprocess.Detailedmechanicaltests including tensile, flexural, impact, and hardness evaluations demonstrated that the optimum enhancementinstrengthwasachievedat15wt.%fibrereinforcement,particularlywith20mm fibres, where improvements in tensile, flexural, and impact strengths were most pronounced. Thermal analysis via thermogravimetric analysis (TGA) indicated that these composites maintain high thermal stability up to 220°C, with only minimal weight loss due to moisture vaporization and subsequent degradation of natural fibre components. Morphological assessments using scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR) analyses further confirmed enhanced fibre matrix adhesion and a reduction in microstructural defects, underpinning the overall performance improvements.

Komal et al. [11] explored the influence of different processing techniques such as direct injection moulding (DIM), extrusion injection moulding (EIM), and extrusion compression moulding (ECM) on the properties of BNF-reinforced PLA bio composites. Using 20 wt.% BNF, the composites were evaluated for their mechanical, thermal, dynamic mechanical, morphological, and crystallinity characteristics. The research found that EIM-processed composites demonstrated superior tensile and flexural strength, crystallinity, and dynamic mechanical performance due to improved fibre–matrix bonding and fibre orientation. DIM composites exhibited the highest impact strength, attributed to fibre pull-out mechanisms, while ECM composites showed the lowest overall mechanical performance due to poor fibre alignmentandfibreclusteringduringmoulding.Thermalstability,hardnessandFTIRanalysis confirmed that processing technique had little effect on chemical composition or thermal degradation behaviour. The study concludes that EIM offers the most favourable balance of strength and process efficiency, highlighting its potential for producing sustainable, high- performance bio composites for automotive and non-structural applications.

Motaleb et al. [15] investigated how pre- and post-treatment methods affect the physical and mechanical properties of BNF nonwoven reinforced polymer composites. Four types of nonwovensfromdifferentpartsofthebananatree namelyouterbark,middlebark,innerbark, and midrib using a wet-laid web formation technique, and subsequently reinforced these with epoxyandpolyestermatricestoproduce eightcompositevariants.Studyexaminedthe effects of chemical modifications, such as alkali treatment to remove impurities, water repellent application to improve hydrophobicity, and gamma radiation to enhance mechanical performance.ComprehensivecharacterizationsusingFTIRspectroscopy andSEMelucidated changes in the chemical and morphological structure of the fibres, leading to improved fibre– matrix adhesion and reduced water absorption. The findings indicate that composites, particularly those made from outer bark fibres and treated optimally, exhibit significantly enhanced tensile and flexural strengths along with lower water absorbency compared to their untreated counterparts.

Kenned et al. [22] proposed an innovative, chemical-free method i.e., needle punching to fabricatehigh-performancenatural-fibrecompositesusinguntreatedBNFsandanunsaturated polyester matrix. By mechanically entangling BNF webs at optimized punch density and penetration depth, the authors achieve composites with 40wt.% fibre content whose tensile andflexuralstrengthsincreaseby36%and33%,respectively,comparedtorandomlyoriented controls.Quasi-staticindentationtestsshowtheirload-bearingcapacity(2420N)andRockwell hardness(87HRRW)rivalthoseofglass-fibrecomposites,whiledynamicmechanicalanalysis (DMA)revealsimprovedstoragemodulusandelevatedglasstransitiontemperature.FTIRand X-ray diffraction (XRD) confirm the preservation of cellulose functional groups and a crystallinity index of 55%, and TGA demonstrates thermal stability up to 260°C. SEM of fracture surfaces correlate the superior mechanical performance to enhanced fibre–matrix interlocking. The study compellingly positions needle-punched BFRPCs as eco-friendly, cost- effective alternatives for helmets, door panels, and lightweight structures.

Subramanya et al. [23] presents a detailed study on the potential of chemically treated short BNFs as reinforcement in epoxy resin composites. Using a hand lay-up method, composites werecreatedwithfibresofvaryinglengths(5mm,8mm,and10mm)at60wt.%loading,and their mechanical and thermal properties were evaluated. The study found that 5 mm treated fibresofferedthebestmechanicalperformanceintermsoftensilestrengthandhardness,while impactstrengthimprovedwithincreasingfibrelength.Mechanicaltestingrevealedthatthe 5mm-fibrecompositesexhibitedthehighesttensilestrength(~63.5MPa,a29%improvement over neat epoxy) and superior hardness, while impact toughness increased with fibre length, peaking at ~27.2J/m for 10mm fibres. Thermal conductivity decreased as fibre length increased (from 0.342W/mK at 5mm to 0.308W/mK at 10mm), reflecting the insulating effect of the BNFs. SEM fractography confirmed good fibre–matrix adhesion after NaOH treatment. The study demonstrates that short BNFs can significantly enhance stiffness, strength, and thermal insulation in high fibre content epoxy composites, with an optimalfibre length of ~5 mm for balanced.

Kusić et al. [29] investigated the viability of using short alkali-treated BNFs to reinforce commonthermoplastics(ABS,HIPSandHDPE),particularlyinapplicationsdominatedbybending loads. The tensile modulus increased progressively with the fibre content across all polymer matrices. In HDPE, the highest stiffness increase was 72.8% compared to the pure matrix, with a 15% fibre content, reaching a tensile modulus of 1.4 GPa. Through a comprehensive display of thermal analyses (TGA, DSC, MFI) and mechanical tests (tensile, flexural, impact, DMA), the authors demonstrate that incorporation of up to 30wt.% BNF yields composites with significantly increased stiffness (e.g., tensile modulus nearly doubled in ABS and HIPS) and improved flexural strength, while thermal transitions remain largely unaffectedand degradation temperatures aremaintainedabovetypical processing ranges. The studyalsohighlightsthetrade-offslikereduced meltflowindexandimpact toughnessaswell as the importance of fibre–matrix adhesion and uniform dispersion to optimize performance.

Boopalan et al. [34] investigated epoxy composites reinforced with raw jute fibre and BNFs. Study examines the effect of different fibre weight ratios on the mechanical properties of fabricatedcompositesthroughtensile,flexural,andimpactstrengthtests.Thecompositeswere fabricatedusingaHLtechniquefollowedbyCM.ThermalbehaviourwasanalysedwithTGA and heat deflection temperature tests. The tensile test was conducted according to ASTM D 638-03 with a test speed of 5 mm/min, while the flexural strength was measured following ASTM D790, maintaining atest speed between 1.3 -1.5 mm/min. Theimpact strength ofthe composite specimens was evaluated using an Izod impact tester as per ASTM D 256. In each test, five specimens were examined to determine the averagevalue. The results indicate that a 50/50weightratioofjutetoBNFyieldsoptimalperformance.SEMresultsrevealedimproved fibre matrix adhesion and minimized voids. The study also demonstrated a reduction in water absorption at the balanced 50/50 ratio. The incorporation of BNF enhanced tensile, flexural, andimpactstrengthssignificantly.Overall,theresearchconcludesthatbalancedhybridization of natural fibres offers robust, thermally stable, and environmentally friendly composite materials.

Komaletal.[35]investigatedtheeffectofchemicaltreatmentonthethermal,mechanical,and degradationbehaviourofBNF-reinforcedpolypropylene(PP)composites.Usinganextrusion- injection moulding process, composites containing 20% by weight BNF both untreated and treatedwith5%NaOHwerefabricated.Alkalinetreatmentwasshowntoenhancefibrematrix adhesion,resultinginmoderateimprovementsintensile,flexural,andimpactstrengths(3.8%, 5.17%, and 11.5%, respectively). TGA revealed increased thermal stability in treated fibres. Degradation studies conducted through water immersion and soil burial for five weeks indicatedthatuntreatedcompositesdegradedmoresignificantly,particularlyundersoilburial, losing up to 17.24% of flexural strength. Treated composites showed improved resistance to environmental degradation, supported by SEM images that confirmed reduced fibre pull-out andmicrocracking.Overall,thestudyhighlightsthatchemicaltreatmentofBNFssignificantly improvesthedurabilityandperformanceofbio-basedcomposites,makingthemmoresuitable for long-term applications in diverse environments.

Bordón et al. [39] evaluated the mechanical performance and environmental impact of BNF reinforced high-density polyethylene (HDPE) composites developed through injection moulding. The researchers explored two fibre processing methods: a chemically treated second-generationfibreandamoresustainablethird-generationfibreobtainedthroughmechanical combing. Mechanical testing showed that the addition of up to 30 wt.% BF improved stiffness, while finite element simulations enabled the reduction of component thickness without compromising performance. Life Cycle Assessment (LCA) revealed that third-generationBFsignificantlyreducedenvironmentalimpactscomparedtobothpureHDPE and chemically treated fibres. The optimized design of a real-world component (an air- conditionermountingsleeve)usingthesebio-compositesdemonstratedlowermaterialuseand carbon footprint, especially at higherBNFcontents. The study highlightsthe value of BNFas a low-impact, high-performance reinforcement alternative for sustainable polymer composite development.

The above literature review emphasizes the potential of utilizing BNF as eco-friendly, sustainablereinforcementmaterialsinpolymercomposites,offeringpromisingapplicationsin various engineering sectors.

V. Conclusions

- BNF-reinforced epoxy composites with 15% fibre content showed the best mechanical properties, including optimal flexural strength, hardness, and impact resistance. Higher fibre content reduced strength. Composites with 15 - 20% BNF also improved thermal stability, with 15% being most effective. BNF fibres offer a sustainable, eco-friendly alternative for use in automotive, construction, textiles, and packaging.
- By using methods such as hand lay-up, compression moulding, and injection moulding, BNFs can be successfully incorporated into polymer matrices to form robust, lightweight composites.
- Treatmentslikealkaline,silane,andacidprocessinghelpimprovethebondingbetweenthe fibres and the matrix, further enhancing the strength and durability of the composites.
- Overall, BNF composites offer a green, cost-effective solution with excellent strength-to- weight ratios and lower environmental impact, making them an appealing choice for industries moving toward sustainable material options.
- In conclusion, the continued development of BNF composites, including advances in surface treatment techniques and processing methods, can play a vital role in replacing conventional, petroleum-based materials.
- With the growing emphasis on environmental responsibility and sustainability, BNF compositesarepoisedtobecomeanimportantcomponentinthegreenmaterialsrevolution, contributing to more sustainable manufacturing practices and eco-conscious product designs.

REFERENCES

[1] Rao, B.L., Y. Makode, A. Tiwari, O. Dubey, S. Sharma, and V. Mishra, *Review on properties of banana fiber reinforced polymer composites.* Materials Today: Proceedings, 2021. **47**: p. 2825-2829.

[2] K R, G. and A. and H S, *Evaluation of mechanical properties of hybridised coir- carbon-basalt reinforced epoxy composites.* Advances in Materials and Processing Technologies, 2025. **11**(1): p. 576-588.

[3] Ashrith, H.S., T.P. Jeevan, and J. Xu, *A Review on the Fabrication and Mechanical Characterization of Fibrous Composites for Engineering Applications.* Journal of Composites Science, 2023. **7**(6): p. 252.

[4] Kiruthika, A., *A review on physico-mechanical properties of bast fibre reinforced polymer composites.* Journal of Building Engineering, 2017. **9**: p. 91-99.

[5] Balaji, A., R. Purushothaman, R. Udhayasankar, S. Vijayaraj, and B. Karthikeyan, *Studyonmechanical,thermalandmorphologicalpropertiesofbananafiber-reinforced epoxy composites.* Journal of Bio-and Tribo-Corrosion, 2020. **6**: p. 1-10.

[6] Akatwijuka,O.,M.A.-H.Gepreel,A.Abdel-Mawgood,M.Yamamoto,Y.Saito,andA.H. Hassanin, *Overview of banana cellulosic fibers: agro-biomass potential, fiber extraction, properties, and sustainable applications.* Biomass Conversion and Biorefinery, 2024. **14**(6): p. 7449-7465.

[7] Bhatnagar, R., G. Gupta, and S. Yadav, *A review on composition and properties of banana fibers.* Cellulose, 2015. **60**: p. 65.

[8] Zin,M.H.,K.Abdan,andM.N.Norizan,*Theeffectofdifferentfiberloadingonflexural and thermal properties of banana/pineapple leaf (PALF)/glass hybrid composite*, in *Structuralhealthmonitoringofbiocomposites,fibre-reinforcedcompositesandhybrid composites*. 2019, Elsevier. p. 1-17.

[9] Kumar, K.S., D. Bhowmik, S. Duraivel, and M. Umadevi, *Traditional and medicinal uses of banana.* Journal of pharmacognosy and phytochemistry, 2012. **1**(3): p. 51-63.

[10] Cadena Ch, E.M., J.M. Vélez R, J. Santa, and V. Otálvaro G, *Natural fibers from plantain pseudostem (Musa paradisiaca) for use in fiber-reinforced composites.* Journal of Natural Fibers, 2017. **14**(5): p. 678-690.

[11] Komal, U.K., M.K. Lila, and I. Singh, *PLA/banana fiber based sustainable biocomposites: A manufacturing perspective.* Composites Part B: Engineering, 2020. **180**: p. 107535.

[12] Badanayak, P., S. Jose, and G. Bose, *Banana pseudostemfiber: A critical review on fiber extraction, characterization, and surface modification.* Journal of natural fibers, 2023. **20**(1): p. 2168821.

[13] Nguyen, T.A. and T.H. Nguyen, *Study on mechanical properties of banana fiber‐reinforced materials poly (lactic acid) composites.* International Journal of Chemical Engineering, 2022. **2022**(1): p. 8485038.

[14] Balaji, A., S. Kannan, R. Purushothaman, S. Mohanakannan, A.H. Maideen, J. Swaminathan, B. Karthikeyan, and P. Premkumar, *Banana fiber and particle-reinforcedepoxybiocomposites:mechanical,waterabsorption,andthermalproperties investigation.* Biomass Conversion and Biorefinery, 2024. **14**(6): p. 7835-7845.

[15] Motaleb, K.A., A. Ahad, G. Laureckiene, and R. Milasius, *Innovative banana fiber nonwoven reinforced polymer composites: pre-and post-treatment effects on physical and mechanical properties.* Polymers, 2021. **13**(21): p. 3744.

[16] Bharath, K., M. Puttegowda, T. YashasGowda, G. Arpitha, S. Pradeep, S.M. Rangappa, and S. Siengchin, *Development of banana fabric incorporated polymer compositesforprintedcircuitboardapplication.*BiomassConversionandBiorefinery, 2024. **14**(11): p. 12599-12612.

[17]Nguyen, T.A. and T.H. Nguyen, *Banana fiber‐reinforced epoxy composites: mechanical properties and fire retardancy.* International Journal of Chemical Engineering, 2021. **2021**(1): p. 1973644.

[18] Zaman,H.U.andM.Beg,*Bananafiberstrands–reinforcedpolymermatrixcomposites.*CompositeInterfaces,2016. **23**(4):p.281-295.

[19] Venkateshwaran, N. and A. Elayaperumal, *Banana fiber reinforced polymer composites-a review.* Journal of Reinforced Plastics and Composites, 2010. **29**(15): p. 2387-2396.

[20] Azwa,Z.,B.Yousif,A.Manalo,andW.Karunasena,*Areviewonthedegradabilityof polymeric composites based on natural fibres.* Materials & Design, 2013. **47**: p. 424- 442.

[21] Satyanarayana, K., K. Sukumaran, P. Mukherjee, C. Pavithran, and S. Pillai, *Natural fibre-polymer composites.* Cement and Concrete composites, 1990. **12**(2): p. 117-136.

[22] Kenned, J.J., K. Sankaranarayanasamy, J. Binoj, and S.K. Chelliah, *Thermo-mechanicalandmorphologicalcharacterizationofneedlepunchednon-wovenbanana fiberreinforcedpolymercomposites.*CompositesScienceandTechnology,2020.**185**:p. 107890.

[23] Subramanya, R., K.G. Satyanarayana, and B. Shetty Pilar, *Evaluation of structural, tensileandthermalpropertiesofbananafibers.*JournalofNaturalFibers,2017.**14**(4):p.485-497.

[24] Guimaraes, J.L., E. Frollini, C. Da Silva, F. Wypych, and K. Satyanarayana, *Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil.* Industrial Crops and Products, 2009. **30**(3): p. 407-415.

[25] Pereira,P.H.F., K.C.C.CarvalhoBenini,C.Y.Watashi,H.J.C.Voorwald,andM.O.H. Cioffi, *Characterizationof high density polyethylene (HDPE) reinforced with banana peel fibers.* 2013.

[26] Ronald Aseer, J., K. Sankaranarayanasamy, P. Jayabalan, R. Natarajan, and K. PriyaDasan, *Morphological,physical,andthermalpropertiesofchemicallytreatedbanana fiber.* Journal of Natural Fibers, 2013. **10**(4): p. 365-380.

[27] Bar, M., H. Belay, R. Alagirusamy, A. Das, and P. Ouagne, *Refining of banana fiber forloadbearingapplicationthroughemulsiontreatmentanditscomparisonwithother traditional methods.* Journal of Natural Fibers, 2022. **19**(13): p. 5956-5973.

[28] Paramasivam, S.K., D. Panneerselvam, D. Sundaram, K.N. Shiva, and U. Subbaraya, *Extraction, characterization and enzymatic degumming of banana fiber.* Journal of Natural Fibers, 2022. **19**(4): p. 1333-1342.

[29] Kusić, D., U. Božič, M. Monzón, R. Paz, and P. Bordón, *Thermal and mechanical characterization of banana fiber reinforced composites for its application in injection molding.* Materials, 2020. **13**(16): p. 3581.

[30] Neelamana, I.K., S. Thomas, and J. Parameswaranpillai, *Characteristics of banana fibers and banana fiber reinforced phenol formaldehyde composites‐macroscale to nanoscale.* Journal of Applied Polymer Science, 2013. **130**(2): p. 1239-1246.

[31] Singh,B.K.,U.K.Komal,Y.Singh,S.S.Banwait,andI.Singh,*Developmentofbanana fiber reinforced composites from plastic waste.* Materials Today: Proceedings, 2021. **44**: p. 2194-2198.

[32] Kumar, R., V. Choudhary, S. Mishra, and I. Varma, *Banana fiber-reinforced biodegradable soy protein composites.* Frontiers of Chemistry in China, 2008. **3**: p. 243-250.

[33] Shahapurkar,K.,S.Ramesh,N.-N.Nik-Ghazali,G.Gebremaryam,G.Kanaginahal,C. Venkatesh, M.E.M. Soudagar, Y. Fouad, and M. Kalam, *Tensile, compressive, and fracture behavior of Habeshian chopped banana/epoxy core sandwich woven banana composite.* Biomass Conversion and Biorefinery, 2024. **14**(17): p. 21553-21564.

[34] Boopalan, M., M. Niranjanaa, and M. Umapathy, *Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites.* Composites Part B: Engineering, 2013. **51**: p. 54-57.

[35] Komal, U.K., V. Verma, T. Ashwani, N. Verma, and I. Singh, *Effect of chemical treatmentonthermal,mechanicalanddegradationbehaviorofbananafiberreinforced polymer composites.* Journal of Natural Fibers, 2020.

[36] Adekunle, K., D. Åkesson, and M. Skrifvars, *Biobased composites prepared by compressionmoldingwithanovelthermosetresinfromsoybeanoilandanatural‐fiber reinforcement.* Journal of applied polymer science, 2010. **116**(3): p. 1759-1765.

[37] Farahani,G.N.,I.Ahmad,andZ.Mosadeghzad,*Effectoffibercontent,fiberlengthand alkali treatment on properties of kenaffiber/UPR composites based on recycled PET wastes.* Polymer-Plastics Technology and Engineering, 2012. **51**(6): p. 634-639.

[38] Chaitanya, A., D.K. Babu, K.B. Narendra, and K. Sumanth, *Investigation on the mechanical properties of banana fiber reinforced polyester composites.* International Journal of Engineering Research and Application, 2016. **6**(9): p. 76-82.

[39] Bordón, P., D. Elduque, R. Paz, C. Javierre, D. Kusić, and M. Monzón, *Analysis of processing and environmental impact of polymer compounds reinforced with banana fiber in an injection molding process.* Journal of Cleaner Production, 2022. **379**: p. 134476.