Contents

1 Mechanical Behaviors of Natural Fiber-Reinforced Polymer Hybrid Composites *1*
Adelani A. Oyeniran and Sikiru O. Ismail
1.1 Introduction *1*
1.2 Concept of Natural Fibers and/or Biopolymers: Biocomposites *3*
1.2.1 Natural Fiber-Reinforced Polymer Composites or Biocomposites *3*
1.2.2 Polymer Matrices *4*
1.3 Hybrid Natural Fiber-Reinforced Polymeric Biocomposites *7*
1.4 Mechanical Behaviors of Natural Fiber-Reinforced Polymer-Based Hybrid Composites *10*
1.4.1 Hybrid Natural FRP Composites *11*
1.4.1.1 Bagasse/Jute FRP Hybrid Composites *11*
1.4.1.2 Bamboo/MFC FRP Hybrid Composites *12*
1.4.1.3 Banana/Kenaf and Banana/Sisal FRP Hybrid Composites *12*
1.4.1.4 Coconut/Cork FRP Hybrid Composites *14*
1.4.1.5 Coir/Silk FRP Hybrid Composites *15*
1.4.1.6 Corn Husk/Kenaf FRP Hybrid Composites *16*
1.4.1.7 Cotton/Jute and Cotton/Kapok FRP Hybrid Composites *16*
1.4.1.8 Jute/OPEFB FRP Hybrid Composites *18*
1.4.1.9 Kenaf/PALF FRP Hybrid Composites *18*
1.4.1.10 Sisal/Roselle and Sisal/Silk FRP Hybrid Composites *19*
1.5 Other Related Properties that Are Dependent on Mechanical Properties *20*
1.5.1 Tribological Behavior *20*
1.5.2 Thermal Behavior *21*
1.6 Progress and Future Outlooks of Mechanical Behaviors of Natural FRP Hybrid Composites *21*
1.7 Conclusions *22*
References *23*

2 Mechanical Behavior of Additive Manufactured Porous Biocomposites *27*
Ramu Murugan and Mohanraj Thangamuthu
2.1 Introduction *27*
2.2 Human Bone *27*
2.3 Porous Scaffold *29*
2.4 Biomaterials for Scaffolds *30*
2.4.1 Required Properties of Biomaterials *30*
2.4.2 Types of Biomaterials *31*
2.4.2.1 Metals *31*
2.4.2.2 Polymers *31*
2.4.2.3 Ceramics *32*
2.4.2.4 Composites *32*
2.5 Additive Manufacturing of Porous Structures *33*
2.5.1 Generic Process of AM *33*
2.5.2 Powder Bed Fusion Process *34*
2.5.3 Fused Deposition Modeling Process *35*
2.5.4 Additive Manufacturing of Porous Biocomposites *35*
2.6 Design of Porous Scaffold *36*
2.6.1 Pore Size *36*
2.6.2 Pore Geometry *37*
2.6.3 Bioceramics as Reinforcement Material *37*
2.7 Mechanical Characterization of Additive Manufactured Porous Biocomposites *38*
2.8 Conclusion *41*
References *41*

3 Mechanical and Dynamic Mechanical Analysis of Bio-based Composites *49*
R.A. Ilyas, S.M. Sapuan, M.R.M. Asyraf, M.S.N. Atikah, R. Ibrahim, Mohd N.F. Norrrahim, Tengku A.T. Yasim-Anuar, and Liana N. Megashah
3.1 Introduction *49*
3.2 Mechanical Properties of Macro-scale Fiber *50*
3.3 Mechanical Properties of Nano-scale Fiber *50*
3.3.1 Factors Affecting Mechanical Properties of Bionanocomposites *50*
3.3.1.1 Fabrication Method *51*
3.3.1.2 Nanocellulose Loading *53*
3.3.1.3 Nanocellulose Dispersion and Distribution *53*
3.3.1.4 Nanocellulose Orientation *53*
3.3.2 The Static Mechanical Properties of Bionanocomposites *54*
3.4 Dynamic Mechanical Analysis (DMA) of Biocomposites *55*
3.4.1 Single Fiber *57*
3.4.1.1 Sugar Palm *57*
3.4.1.2 Bamboo *57*

3.4.1.3 Kenaf *59*
3.4.1.4 Alfa *59*
3.4.1.5 Carnauba *59*
3.4.1.6 Pineapple Leaf Fiber (PALF) *60*
3.4.1.7 Oil Palm Fiber (OPF) *60*
3.4.1.8 Red Algae *60*
3.4.1.9 Banana *61*
3.4.1.10 Flax *62*
3.4.1.11 Jute *62*
3.4.1.12 Hemp *63*
3.4.1.13 Waste Silk Fiber *63*
3.4.1.14 Henequen *64*
3.4.2 Hybrid Fiber *64*
3.4.2.1 Sisal/Oil Palm *64*
3.4.2.2 Coir/PALF *65*
3.4.2.3 Kenaf/PALF *65*
3.4.2.4 Palmyra Palm Leaf Stalk Fiber (PPLSF)/Jute *66*
3.4.2.5 Oil Palm Empty Fruit Bunch (OPEFB)/Cellulose *66*
3.5 Dynamic Mechanical Properties of Bionanocomposites *66*
3.5.1 The Dynamic Mechanical Properties of Bionano composites *67*
3.6 Conclusion *68*
References *68*

4 Physical and Mechanical Properties of Biocomposites Based on Lignocellulosic Fibers *77*
Nadir Ayrilmis, Sarawut Rimdusit, Rajini Nagarajan, and M.P. Indira Devi
4.1 Introduction *77*
4.2 Major Factors Influencing Quality of Biocomposites *82*
4.2.1 Selection of Natural Fibers *82*
4.2.2 Effect of Fiber/Particle Size on the Physical and Mechanical Properties of Biocomposites *85*
4.2.3 Effect of Filler Content on the Mechanical Properties of Biocomposites *88*
4.2.4 Compatibility Between Natural Fiber/Polymer Matrix and Surface Modification *91*
4.2.5 Type of Polymer Matrix *95*
4.2.6 Processing Conditions in the Manufacture of Biocomposite *96*
4.2.7 Presence of Voids and Porosity *98*
4.2.8 Nanocellulose-Reinforced Biocomposites *98*
4.2.8.1 Preparation and Properties of Cellulose Nanofibers *101*
4.2.8.2 Industrial Applications of Cellulose Nanofibers *101*
4.3 Conclusions *103*
References *103*

5 Machinability Analysis on Biowaste Bagasse-Fiber-Reinforced Vinyl Ester Composite Using *S/N* Ratio and ANOVA Method *109*
Balasubramaniam Stalin, Ayyanar Athijayamani, and Rajini Nagarajan
5.1 Introduction *109*
5.2 Experimental Methodology *111*
5.2.1 Materials *111*
5.2.2 Specimen Preparation *111*
5.2.3 Machining of the Composite Specimen *111*
5.2.4 Selection of Orthogonal Array *111*
5.2.5 Development of Multivariable Nonlinear Regression Model *113*
5.3 Results and Discussion *114*
5.3.1 Influence of Machining Parameters on Thrust Force and Torque *114*
5.3.2 *S*/*N* Ratio *115*
5.3.3 ANOVA *115*
5.3.4 Correlation of Machining Parameters with Responses *116*
5.3.5 Confirmation Test *117*
5.4 Conclusions *118*
References *118*

6 Mechanical and Dynamic Properties of Kenaf-Fiber-Reinforced Composites *121*
Brijesh Gangil, Lalit Ranakoti, and Pawan K. Rakesh
6.1 Introduction *121*
6.2 Mechanical Properties of Kenaf-Fiber-Reinforced Polymer Composite *122*
6.3 Dynamic Mechanical Analysis *124*
6.4 Storage Modulus (E') of Kenaf Fiber–Polymer Composite *125*
6.5 Loss Modulus (E'') of Kenaf Fiber–Polymer Composite *125*
6.6 Damping Factor (Tan δ) *126*
6.7 Glass Transition Temperatures (T_g) *127*
6.8 Conclusion *130*
References *131*

7 Investigation on Mechanical Properties of Surface-Treated Natural Fibers-Reinforced Polymer Composites *135*
Sabarish Radoor, Jasila Karayil, Aswathy Jayakumar, and Suchart Siengchin
7.1 Introduction *135*
7.2 Mechanical Properties of Natural Fibers *135*
7.3 Drawbacks of Natural Fibers *136*
7.4 Surface Modification of Natural Fibers *137*
7.4.1 Chemical Treatment *137*
7.4.2 Alkaline Treatment *137*
7.4.3 Silane Treatment *140*
7.4.4 Acetylation Treatment *143*

7.4.5 Benzylation Treatment *145*
7.4.6 Peroxide Treatment *146*
7.5 Maleated Coupling Agents *147*
7.5.1 Isocyanate *148*
7.5.2 Permanganate Treatment *150*
7.5.3 Stearic Acid Treatment *151*
7.5.4 Physical Treatment *152*
7.5.5 Plasma Treatment *152*
7.5.6 Corona Treatment *154*
7.5.7 Ozone Treatment *155*
7.6 Summary *156*
References *156*

8 Mechanical and Tribological Characteristics of Industrial Waste and Agro Waste Based Hybrid Composites *163*
Vigneswaran Shanmugam, Uthayakumar Marimuthu, Veerasimman Arumugaprabu, Sundarakannan Rajendran, and Rajendran Deepak Joel Johnson
8.1 Introduction *163*
8.2 Materials and Methods *164*
8.2.1 Scanning Electron Microscopy (SEM) *166*
8.3 Result and Discussion *166*
8.3.1 Effect of Chemical Treatment on Fiber *166*
8.3.2 Mechanical Behavior *167*
8.3.3 Erosion Behavior *169*
8.3.3.1 Effect of Fiber Treatment on Erosion Rate *169*
8.3.3.2 Effect of Red Mud Addition on Erosion Rate *170*
8.3.3.3 Effect of Impact Angle on Erosion Rate *170*
8.4 Conclusion *173*
References *173*

9 Dynamic Properties of Kenaf-Fiber-Reinforced Composites *175*
Rashed Al Mizan, Nur N. Akter, and Mohammad I. Iqbal
9.1 Introduction *175*
9.2 Manufacturing Techniques for Kenaf-Fiber-Reinforced Composites *176*
9.3 Characterization *177*
9.3.1 Dynamic Mechanical Analysis (DMA) *178*
9.3.2 Thermogravimetric Analysis (TGA) *178*
9.3.3 Vibration-Damping Testing *178*
9.3.4 Acoustic Properties *179*
9.4 Overview of the Dynamics Properties of Kenaf-Fiber-Reinforced Composite *179*
9.4.1 Dynamic Mechanical Properties (DMA) *180*
9.4.2 TGA Analysis of Composites *184*

9.4.3 Acoustic Properties *186*
9.5 Conclusion *187*
References *187*

10 Effect of Micro-Dry-Leaves Filler and Al-SiC Reinforcement on the Thermomechanical Properties of Epoxy Composites *191*
Mohit Hemath, Govindrajulu Hemath Kumar, Varadhappan Arul Mozhi Selvan, Mavinkere R. Sanjay, and Suchart Siengchin
10.1 Introduction *191*
10.2 Materials and Methods *193*
10.2.1 Materials *193*
10.2.2 Production of Al-SiC Nanoparticles *193*
10.2.3 Fabrication of Epoxy Composites *194*
10.2.4 Epoxy Composite Characterization *194*
10.2.4.1 Porosity, Density, and Volume Fraction *194*
10.2.4.2 Tensile Properties *194*
10.2.4.3 Flexural Properties *194*
10.2.4.4 Impact Strength *195*
10.2.4.5 Dynamic Mechanical Analysis (DMA) *195*
10.2.4.6 Morphological Properties *195*
10.3 Results and Discussion *195*
10.3.1 Quality of Fabrication and Volume Fraction of Epoxy Composites *195*
10.3.2 Tensile Characteristics *196*
10.3.3 Flexural Characteristics *197*
10.3.4 Impact Characteristics *198*
10.3.5 Dynamic Mechanical Analysis *199*
10.3.5.1 Storage Modulus *199*
10.3.5.2 Loss Modulus *200*
10.3.5.3 Damping Factor *201*
10.3.6 Morphological Characteristics *201*
10.4 Conclusion *201*
References *202*

11 Effect of Fillers on Natural Fiber–Polymer Composite: An Overview of Physical and Mechanical Properties *207*
Annamalai Saravanakumaar, Arunachalam Senthilkumar, and Balasundaram Muthu Chozha Rajan
11.1 Introduction *207*
11.2 Influence of Cellulose Micro-filler on the Flax, Pineapple Fiber-Reinforced Epoxy Matrix Composites *208*
11.3 Influence of Sugarcane Bagasse Filler on the Cardanol Polymer Matrix Composites *208*
11.4 Influence of Sugarcane Bagasse Filler on the Natural Rubber Composites *209*
11.5 Influence of Fly Ash on Wood Fiber Geopolymer Composites *210*

11.6 Influence of Eggshell Powder/Nanoclay Filler on the Jute Fiber Polyester Composites *211*
11.7 Influence of *Portunus sanguinolentus* Shell Powder on the Jute Fiber–Epoxy Composite *212*
11.8 Influence of Nano-SiO_2 Filler on the *Phaseolus vulgaris* Fiber–Polyester Composite *214*
11.9 Influence of Aluminum Hydroxide ($Al(OH)_3$) Filler on the Vulgaris Banana Fiber–Epoxy Composite *215*
11.10 Influence of Palm and Coconut Shell Filler on the Hemp–Kevlar Fiber–Epoxy Composite *216*
11.11 Influence of Coir Powder Filler on Polyester Composite *217*
11.12 Influence of $CaCO_3$ (Calcium Carbonate) Filler on the Luffa Fiber–Epoxy Composite *217*
11.13 Influence of Pineapple Leaf, Napier, and Hemp Fiber Filler on Epoxy Composite *218*
11.14 Influence of Dipotassium Phosphate Filler on Wheat Straw Fiber–Natural Rubber Composite *220*
11.15 Influence of Groundnut Shell, Rice Husk, and Wood Powder Fillers on the *Luffa cylindrica* Fiber–Polyester Composite *220*
11.16 Influence of Rice Husk Fillers on the *Bauhinia vahlii* – Sisal Fiber–Epoxy Composite *221*
11.17 Influence of Areca Fine Fiber Fillers on the *Calotropis gigantea* Fiber Phenol Formaldehyde Composite *221*
11.18 Influence of Tamarind Seed Fillers on the Flax Fiber–Liquid Thermoplastic Composite *223*
11.19 Influence of Walnut Shell, Hazelnut Shell, and Sunflower Husk Fillers on the Epoxy Composites *223*
11.20 Influence of Waste Vegetable Peel Fillers on the Epoxy Composite *224*
11.21 Influence of *Clusia multiflora* Saw Dust Fillers on the Rubber Composite *224*
11.22 Influence of Wood Flour Fillers on the Red Banana Peduncle Fiber Polyester Composite *225*
11.23 Influence of Wood Dust Fillers (Rosewood and Padauk) on the Jute Fiber–Epoxy Composite *225*
11.24 Summary *226*
11.25 Conclusions *226*
References *231*

12 Temperature-Dependent Dynamic Mechanical Properties and Static Mechanical Properties of *Sansevieria cylindrica* Reinforced Biochar-Tailored Vinyl Ester Composite *235*
Rajendran Deepak Joel Johnson, Veerasimman Arumugaprabu, Rajini Nagarajan, Fernando G. Souza, and Vigneswaran Shanmugam
12.1 Introduction *235*
12.2 Materials and Method *236*

12.2.1 Materials *236*
12.2.2 Biochar Characterization *238*
12.2.2.1 Particle Size Analyzer *238*
12.2.2.2 X-ray Diffraction *238*
12.2.2.3 FTIR Spectroscopy *238*
12.2.3 Composite Fabrication *239*
12.2.4 Dynamic Mechanical Analysis (DMA) *239*
12.2.5 Tensile Testing *239*
12.2.6 Flexural Testing *240*
12.2.7 Impact Testing *240*
12.2.8 Scanning Electron Microscopy *240*
12.3 Results and Discussion *240*
12.3.1 Biochar Characterization *240*
12.3.1.1 Particle Analyzer *240*
12.3.1.2 Fourier Transform (InfraRed) Spectroscopy *240*
12.3.1.3 X-ray Diffraction *242*
12.3.2 Dynamic Mechanical Analysis *243*
12.3.3 Tensile Tests *247*
12.3.4 Flexural Tests *248*
12.3.5 Impact Tests *249*
12.4 Conclusions *251*
References *251*

13 Development and Sustainability of Biochar Derived from Cashew Nutshell-Reinforced Polymer Matrix Composite *255*
Rajendren Sundarakannan, Vigneswaran Shanmugam, Veerasimman Arumugaprabu, Vairavan Manikandan, and Paramasivan Sivaranjana
13.1 Introduction *255*
13.2 Materials and Methods *257*
13.2.1 Biochar Preparation *257*
13.2.2 Composite Preparation *257*
13.2.3 Mechanical Testing *258*
13.3 Results and Discussion *258*
13.3.1 Tensile Strength *258*
13.3.2 Flexural Strength *259*
13.3.3 Impact Strength *260*
13.3.4 Hardness *260*
13.3.5 Failure Analysis of Cashew Nutshell Waste Extracted Biochar-Reinforced Polymer Composites *261*
13.3.5.1 Tensile Strength Failure Analysis *261*
13.3.5.2 Flexural Strength Failure Analysis *262*
13.3.5.3 Impact Strength Failure Analysis *262*
13.4 Conclusion *263*
References *263*

14 Influence of Fiber Loading on the Mechanical Properties and Moisture Absorption of the Sisal Fiber-Reinforced Epoxy Composites *265*
Banisetti Manoj, Chandrasekar Muthukumar, Chennuri Phani Durga Prasad, Swathi Manickam, and Titus I. Benjamin
14.1 Introduction *265*
14.1.1 Sisal Fibers *265*
14.1.2 Fiber Parameters Affecting Mechanical Properties of the Composite *266*
14.2 Materials and Methods *266*
14.2.1 Materials *266*
14.2.2 Fabrication Method *266*
14.2.3 Characterization *266*
14.2.3.1 Tensile Test *266*
14.2.3.2 Flexural Test *267*
14.2.3.3 Moisture Diffusion *267*
14.3 Results and Discussion *267*
14.3.1 Tensile Properties *267*
14.3.2 Flexural Properties *269*
14.3.3 Water Absorption *271*
14.4 Conclusion *272*
References *272*

15 Mechanical and Dynamic Properties of Ramie Fiber-Reinforced Composites *275*
Manickam Ramesh, Lakshminarasimhan Rajeshkumar, and Devarajan Balaji
15.1 Introduction *275*
15.2 Mechanical Strength of Ramie Fiber Composites *277*
15.3 Dynamic Properties of Ramie Fiber Composites *281*
15.3.1 Temperature Influence *283*
15.3.2 Storage Modulus *283*
15.3.3 Viscous Modulus *284*
15.3.4 Damping Factor *284*
15.4 Conclusion *288*
References *289*

16 Fracture Toughness of the Natural Fiber-Reinforced Composites: A Review *293*
Haasith Chittimenu, Monesh Pasupureddy, Chandrasekar Muthukumar, Senthilkumar Krishnasamy, Senthil Muthu Kumar Thiagamani, and Suchart Siengchin
16.1 Introduction *293*
16.1.1 Fracture Toughness Tests *294*
16.1.2 Mode-I Loading *296*
16.1.2.1 Double Cantilever Beam Method (DCB) *296*

16.1.2.2 Compact Tensile Method (CT) *296*
16.1.2.3 Single-Edge Notch Bend Test (SENB) *296*
16.1.3 Mode-II Loading *297*
16.1.3.1 End-Notched Flexure Test (ENF) *297*
16.1.4 Mode-III Loading *297*
16.1.4.1 Split Cantilever Beam Method (SCB) *297*
16.1.4.2 Edge Crack Torsion Test (ECT) *298*
16.1.4.3 Mixed Mode Bend Test (MMB) *298*
16.2 Factors Affecting the Fracture Energy of the Biocomposites *298*
16.2.1 Fiber Parameters *298*
16.2.2 Hybridization *299*
16.2.3 Fiber Treatment *299*
16.2.4 Aging *301*
16.3 Conclusion *302*
Acknowledgments *302*
References *302*

17 Dynamic Mechanical Behavior of Hybrid Flax/Basalt Fiber Polymer Composites *305*
Arun Prasath Kanagaraj, Amuthakkannan Pandian, Veerasimman Arumugaprabu, Rajendran Deepak Joel Johnson, Vigneswaran Shanmugam, and Vairavan Manikandan
17.1 Introduction *305*
17.2 Materials and Methods *307*
17.2.1 Materials *307*
17.2.2 Fabrication of Composites *307*
17.2.3 Dynamic Mechanical Analysis *307*
17.3 Result and Discussion *308*
17.3.1 Damping Factor (Tan δ) Response of Basalt/Flax Fiber Composite *308*
17.3.2 Storage Modulus (E′) Response of Basalt/Flax Fiber Composite *308*
17.3.3 Loss Modulus Performance of Basalt/Flax Fiber Composites *309*
17.4 Conclusions *309*
Acknowledgments *310*
References *310*

Index *313*