Composites Science and Technology

K. Palanikumar
Rajmohan Thiagarajan
B. Latha *Editors*

Bio-Fiber Reinforced Composite Materials

Mechanical, Thermal and Tribological Properties

Springer

Composites Science and Technology

Series Editor

Mohammad Jawaid, Laboratory of Biocomposite Technology, Universiti Putra Malaysia, INTROP, Serdang, Malaysia

Composites Science and Technology (CST) book series publishes cutting edge research monographs (both edited and authored volumes) comprehensively covering topics shown below:

- Composites from agricultural biomass/natural fibres include conventional composites-Plywood/MDF/Fiberboard
- Fabrication of Composites/conventional composites from biomass and natural fibers
- Wood, and Wood based materials
- Chemistry and biology of Composites and Biocomposites
- Modelling of damage of Composites and Biocomposites
- Failure Analysis of Composites and Biocomposites
- Structural Health Monitoring of Composites and Biocomposites
- Durability of Composites and Biocomposites
- Thermal properties of Composites and Biocomposites
- Flammability of Composites and Biocomposites
- Tribology of Composites and Biocomposites
- Bionanocomposites and Nanocomposites
- Applications of Composites, and Biocomposites

To submit a proposal for a research monograph or have further inquries, please contact springer editor, Ramesh Premnath (ramesh.premnath@springer.com).

More information about this series at https://link.springer.com/bookseries/16333

K. Palanikumar · Rajmohan Thiagarajan · B. Latha
Editors

Bio-Fiber Reinforced Composite Materials

Mechanical, Thermal and Tribological Properties

Springer

Editors
K. Palanikumar
Department of Mechanical Engineering
Sri Sairam Institute of Technology
Chennai, Tamil Nadu, India

B. Latha
Department of Computer Science
and Engineering
Sri Sai Ram Engineering College
Chennai, India

Rajmohan Thiagarajan
Department of Mechanical Engineering
Sri Chandrasekharendra Saraswathi Viswa
Mahavidyalaya
Kanchipuram, Tamil Nadu, India

ISSN 2662-1819 ISSN 2662-1827 (electronic)
Composites Science and Technology
ISBN 978-981-16-8898-0 ISBN 978-981-16-8899-7 (eBook)
https://doi.org/10.1007/978-981-16-8899-7

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Global environmental concerns and an increased awareness of renewable green resources have led to considerable effort in providing biodegradable composite and eco-friendly materials for the future generations. This has spurred the researchers of different domains to collaborate in developing a flexible and sustainable process for manufacturing the environment-friendly composite. As an outcome of it, Bio-fiber composites become an attractive alternative to synthetic fiber reinforced composites owing to their eco-friendly nature, strength, low cost and biodegradability. On the top of that, the use of bio-fiber in composites has led to a reduction in greenhouse gas emissions and carbon footprint of composites. Correspondingly, this book provides a detailed overview of a wide range of bio-fibers, their use as reinforcements in composites and their overall performance. Also, this book aims at exploring the applications of composites from bio-fiber for the industrial, medicine and domestic applications by assessing the suitability of bio-fibre composites for specific application. Additionally, it focuses on the research work carried out by various investigators for synthesizing the bio-fiber-based composites for using them in the engineering fields. In this book, experimental investigations are carried out to evaluate the machining performances on the bio-fiber reinforced composite materials. Besides, the influence of various factors like fiber content, stacking, fabrication methods and other manufacturing process parameters on the mechanical and microstructural properties are examined in this book. Similarly, it also explains the pretreatment methods by several researchers to enhance various physical properties of the bio-fiber reinforced composites. An overview of the Dynamic Mechanical Analysis (DMA) of bio-fiber reinforced composites including the effect of different bio-fibre, chemical treatment, fillers, matrix and compositions is presented to reflect on its multifunction purposes. Likewise, this book summarizes the main techniques used for thermal analysis of bio-fibre to assess thermal properties of bio-fibre composite materials. As well, it focuses on the wear performance of bio-fibre composites using a mathematical model. Mainly, it outlines the challenges in the development of bio-composites towards sustainability. Predominantly, it provides an in-depth look at bio-fibre and their bio-composites to lead the researchers in the right direction.

Chennai, India K. Palanikumar
Kanchipuram, India Rajmohan Thiagarajan
Chennai, India B. Latha

Contents

Bio Fibre Composites: Mechanical Characterization

Bio Fibre Composites: Thermal Characterization

About the Editors

Dr. K. Palanikumar is presently Professor and Principal, Sri Sai Ram Institute of Technology, Chennai, India. He completed his Masters Degree in Production Engineering with University FIRST RANK from Annamalai University and obtained Ph.D. Degree in Mechanical Engineering from Anna University, Chennai, Tamilnadu, India. He is involved in Teaching, Research, Development, and Innovation in the field of higher technical education. He is among the world's *top* 2% of *scientists* on a list compiled by *Stanford* University. He has numerous journal publications to his credit as well as several awards, including the National Best teacher award namely AICTE-Visvesvaraya Best Teacher award from Government of India and a Global Peer Review Award from Publons Web of Science. He has also published/presented more than 400 papers in international and national journals/conferences. His Google Scholar h-index is 51. He is Life Member of Indian Tribology Society of India, Indian Society for Non-Destructive testing (ISNT), Indian Welding Society, Indian Society for Technical Education, and Fellow of Institution of Engineers (India) and Indian Institution of Production Engineers. He is Associate Editor of "Journal of Modern Manufacturing Technology" and "International Journal of Materials Forming and Machining Processes (IJMFMP)." His current area of research includes machining of composite materials, modern manufacturing, optimization, simulation, and modeling. He has visited USA, Singapore, Thailand, and Malaysia.

Dr. Rajmohan Thiagarajan is currently working as Associate Professor and Head for the Department of Mechanical Engineering, SCSVMV Deemed to be University, Kancheepuram. He obtained his Bachelors in Mechanical Engineering from the University of Madras and Masters in Production Engineering from Annamalai University, Chidambaram. He did his research in the area of machining of composites and received his doctoral degree from SCSVMV Deemed to be University. His major areas of research include material processing, machining, and tribological behaviour of composite materials. He has published more than 75 research articles in refereed international journals and conferences, and he is also serving as Editorial Review Board Member for several journals in Elsevier, Sage, Taylor & Francis, and many other reputed publications. He has more than 25 years of teaching experience and has more than 8 research scholars under guidance. Dr. T. Rajmohan is currently working as Associate Professor and Head for the Department of Mechanical Engineering, SCSVMV Deemed to be University, Kancheepuram. He obtained his Bachelors in Mechanical Engineering from the University of Madras and Masters in Production Engineering from Annamalai University, Chidambaram. He did his research in the area of machining of composites and received his doctoral degree from SCSVMV Deemed to be University. His major areas of research includes material processing, machining, and tribological behavior of composite materials. He has published more than 75 research articles in refereed international journals and conferences, and he is also serving as Editorial Review Board Member for several journals in Elsevier, Sage, Taylor & Francis, and many other reputed publications. He has more than 20 years of teaching experience and has more than 8 research scholars under guidance.

Dr. B. Latha is currently working as Professor and Head of the Department, in the Department of Computer Science and Engineering, Sri Sairam Engineering College, Chennai, India. She completed her bachelor's in Computer Science and Engineering from Annamalai University, India in 1998 and received her Master's in Computer Science and Engineering from Sathyabama University, India in 2005 andcompleted her Doctorate Degree in the Faculty of Information and Communication Engineering, Anna University Chennai, India in 2010. She has more than 23 years of Experience in Teaching and Research. She has produced 10 Ph.D. scholars as supervisor. She has published/presented more than 100 papers in international and national journals/conferences. She is Life Member of Indian Society for Technical Education, Fellow Member of Institution of Engineers (India), and Member of Computer Society of India. Her current research interest includes artificial intelligence, machining and processing of composite materials, computer-aided modeling, and optimization.

Bio Fibre Composites: Introduction and Applications

Bio-fibre Reinforced Composites: Mechanical, Thermal and Tribological Properties and Industrial Applications—An Introduction

K. Palanikumar, T. Rajmohan, and B. Latha

Abstract The usage of composite materials in engineering has become unavoidable due to the enrichment in properties, drop in the manufacturing cost and suitability to many applications. The features of the polymer composite mainly depend on the choice and composition of reinforcement. Bio fibre reinforcements have confirmed excellent properties, application, and cost in the current situation. The excellent accessibility and availability of bio fibres are the primary motivation for developing new attention in sustainable technology. Bio fibres are a renewable resource that has been replenished for many years by nature and human creativity. The enormous disparity in qualities and characteristics of bio fibre reinforced composites makes using them a difficult task. The purpose of this chapter is to highlight and to give a broad review of recent progress and the options for the future. The present book covers tribological and thermal properties of bio fibres for polymeric resins and explains the different pre-treatment methods used by the researchers for the enhancement. It will provide an introduction about the bio fibres and their bio-composites and point researchers in the right direction.

Keywords Bio-fibers · Natural fibers · Applications · Natural fiber composites · Renewable · Biodegradable · Polymers

K. Palanikumar (✉)
Sri Sai Ram Institute of Technology, Chennai, India

T. Rajmohan
Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya Enathur, Kanchipuram 631561, India

B. Latha
Department of Computer Science Engineering, Sri Sairam Engineering College, Chennai, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_1

1 Introduction

In the growing world, there is an increase in awareness towards conserving the environment, this awareness towards the environment made all the engineering fields continue their research towards developing materials to be more environmentally friendly, bio-degradable and sustainable. Researchers have seen bio-composites as hope towards saving the environment. To bolster their hopes, bio-fibres have shown higher strengths, stiffness and fatigue characteristics. Over the last two decades, there has been much research in natural composites to find alternatives to replace conventional reinforcements like glass, carbon aramid, and boron reinforcements in various engineering applications. These conventional reinforcements have disadvantages like increased production costs, harmful environmental effects etc. To overcome these disadvantages, natural fibres have been the alternative. Natural Fiber Composites have shown their trustworthiness in showing good mechanical properties, lower density, lower weight, environmental reliability, abundant availability and relatable lower production and processing costs.

2 Natural Fibers

Natural fibres are made from various sections of plants, trees, and geographies and are produced and offered by nature. Natural fibre, on the other hand, refers to fibres that are not synthetic. According to where they came from (animals, minerals, or plants sources).

All other types of cellulose fibres are among the plants that produce them (roots and wood). Natural plant fibres are entirely biodegradable and made solely from vegetal sources. Banana, coir, flax, hemp, jute, pineapple, and sisal are just a few examples of plant fibres that have found use as industrial materials.

3 Classification of Natural Fibres

Cotton, flax, and jute are some of the most common vegetable fibres (cellulose-base). Animal (protein-based). Asbestos is a significant mineral fibre. The natural fiber based on the availability is illustrated in (Fig. 1).

3.1 Plant Fibres

Based on where they come from in the plant, each comprises a single, long, narrow cell. Bastfibres are made up of overlapping cells found in the interior bast tissue of some plant stems, such as flax, hemp, jute, and ramie. Fibres found in the fibrovascular system of leaves include abaca, henequen, and sisal. All vegetable fibres are mostly made up of cellulose, but they also contain different levels that must be removed or decreased during processing.

3.2 Abaca

It is a leaf fibre made up of long, thin cells that sustain the leaf's structure. Abaca is renowned for its high mechanical strength, buoyancy, saltwater resistance,and long fibre lengths of up to 3 m. Fine, glossy, light beige, and very strong abaca are the best grades.

3.3 Coir

Coir has the unique lignin content of all vegetable fibres, making it more durable but less flexible than cotton and unsuitable for dyeing. Coir has a lower tensile strength than abaca, but it is resistant to microbial action and saltwater damage. Coir is a coarse, short fibre in ropes, mattresses, brushes, geotextiles, and automotive seats. It is derived from the outer shell of coconuts (Fig. 1).

3.4 Cotton

It is almost entirely made of cellulose, and it is soft and breathable, making it the most well-known natural fibre on the planet. The diameter of the fibres ranges from 11 to 22 microns, while the length ranges from 10 to 65 mm. Cotton absorbs moisture quickly, making it comfortable to wear in hot weather, and its high tensile strength in washing solutions makes it simple to wash. Cotton is the most frequently used natural fibre on the planet, and it is still the unquestioned "monarch" of the textiles industry.

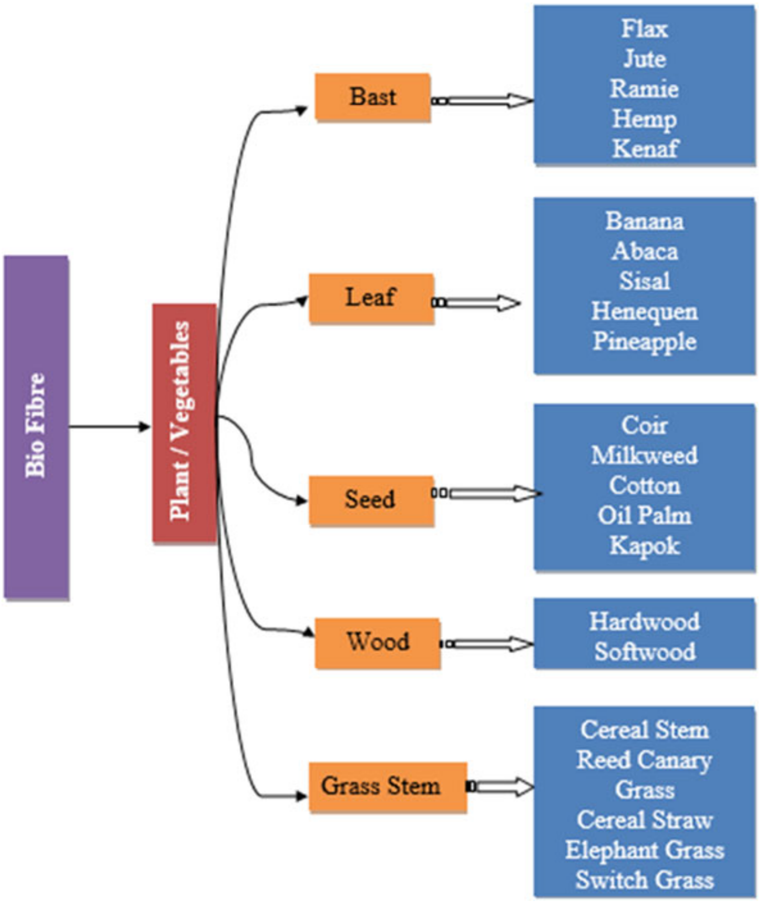


Fig. 1 Natural fiber classification

3.5 Flax

Flax fibre, like cotton, is sharper and stiffer to handle, as well as more wrinkle-resistant. Flax filaments can be up to 90 cm long and have a diameter of 12 to 16 microns. Linen is cool to wear in hot weather because it absorbs and releases water fast. Flax was one of the earliest vegetable fibres to be harvested, spun, and woven into textiles. It is one of nature's most muscular vegetable fibres. Figure 2 shows some of the natural fibers used in nature.

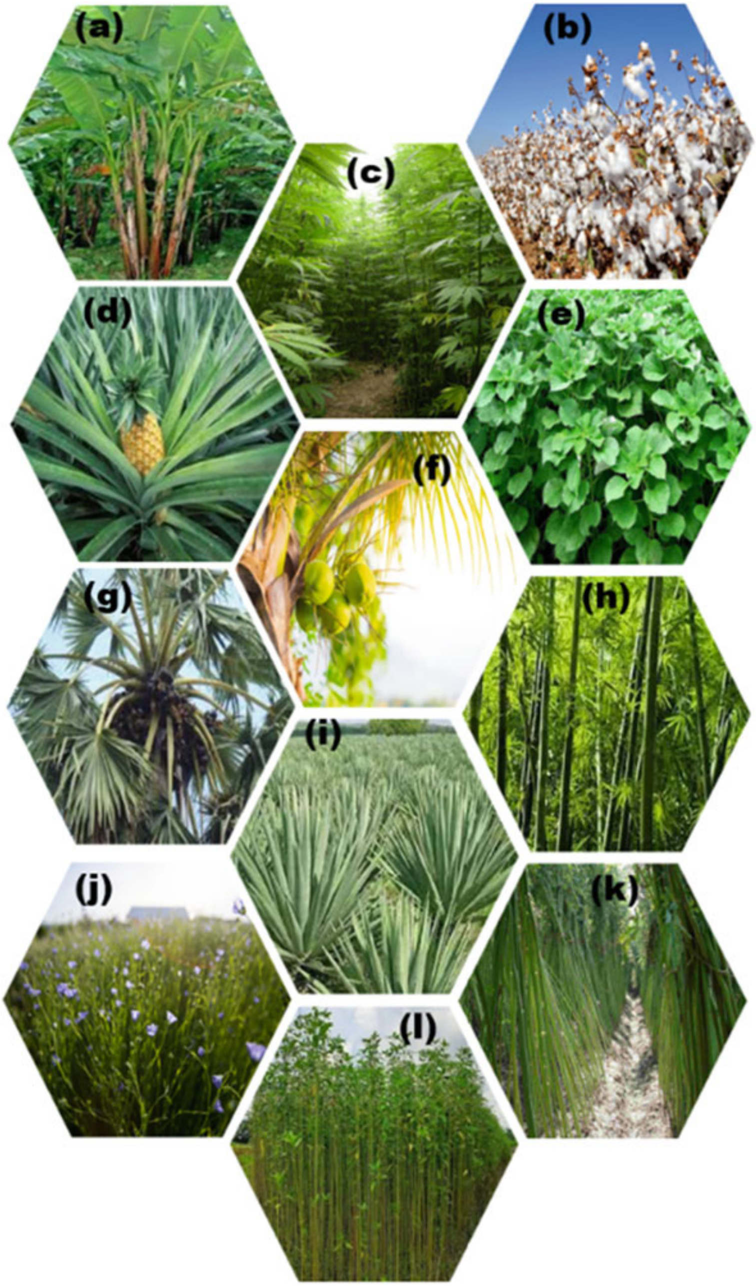


Fig. 2 Fibre plants **a** Abaca; **b** Cotton; **c** Hemp; **d** Pineapple; **e** Ramie; **f** Bamboo; **g** Palm; **h** Bamboo; **i** Sisal; **j** Flax; **k** Kenaf; **l** Jute

3.6 Hemp

Hemp fibres are roughly 70% cellulose and contain low levels of lignin, making them long, strong, and durable (around 8–10 per cent). The diameter of the fibres ranges from 16 to 50 microns. Hemp fibre transmits heat efficiently, resists mildew well, blocks ultraviolet light, and has inherent antibacterial characteristics. Lignin levels are higher in shorter, woody core fibres ("tow"). Hemp is being utilised in agricultural textiles, automobile panels and fiberboard, and "cottoned" apparel since it is easy to grow without agrochemicals.

3.7 Jute

Jute, often known as the "golden fibre," is a long, soft, and lustrous fibre with a diameter of 17 to 20 microns and 1 to 4 m. It is one of the most strong vegetable fibres found in nature, second only to cotton in volume produced. Jute is an excellent insulator and anti-static material. As well as a low thermal conductivity and moderate moisture regain. Jute fibre threads are used in sackcloth worldwide, sustaining the livelihoods of millions of small farmers.

3.8 Ramie

It is white with a soft, absorbent and dense like flax but coarser (25–30 microns). It has poor elasticity and dyes quickly, making it one of the most potent natural fibres. Ramie strands can be as long as 190 cm, with individual cells measuring up to 40 cm. Ramie is brittle due to trans-fibre cracks, which allow for ventilation but make her fragile. Ramie is a lightweight, smooth fabric created for summer that is seldom known outside of the East Asian countries that produce it.

3.9 Sisal

Sisal fibre is lustrous and creamy white, measuring up to 1 m in length and 200 to 400 microns in diameter. It is a coarse, stiff fibre that cannot be used in textiles or clothes. On the other hand, robust, long-lasting, and elastic quickly resists saltwater damage. Sisal replaces glass fibres in composite materials used to create vehicles and furniture because it is too coarse for clothing and upholstery.

4 Applications

Because of its good qualities have a huge potential for replacing present synthetic polymer– or glass fibre–reinforced materials. According to current indications, industry interest in natural fibre composites will continue to expand over the world.

Table 1 The qualities of various commonly used plant and synthetic fibres have been compiled [4]

Fibre	Tensile strength (MPa)	Elongation (%)	Density (g/cm^3)	Young's modulus (GPA)
B. Mori silk	208.45	19.55	1.33	6.1
Abaca	430–760	3–10	1.5	12
Banana	529–914	3	–	27–32
Areca	147–322	10.2–13.15	0.7–0.8	1.12–3.15
Cura 1.4	500–1150	3.7–4.3		11.8
Bagasse	290	–	1.25	17
Bamboo	140–230	–	0.6–1.1	11–17
Henequen	430–570	3.7–5.9	1.2	10.1–16.3
Wood	1000	–	1.5	40
Coir	175	30	1.2	4.0–6.02
Oil palm	248	3.2	0.7–1.55	25
Cotton	287–597	7.0–8.0	1.5–1.6	5.5–12.6
Flax	345–1035	2.7–3.2	1.5	27.6
Kenaf	930	1.5	1.4	53
Piassava	134–143	7.8–21.9	1.4	1.07–4.59
Hemp	690	1.6	1.48	70
Tussah silk	248.77	33.48	1.32	5.79
Isora	500–600	5–6	1.2–1.3	–
Spider silk	875–972	17–18	–	11–13
Jute	393–773	1.5–1.8	1.3	26.5
Twisted B.mori silk	156.27	20.57		3.82
Sisal	511–635	2.0–2.5	1.5	9.4–22.0
Nettle	650	1.7	–	38
Carbon	4000	1.4–1.8	1.4–1.75	230–240
Half	180–1627	1.6–14.5	0.8–1.6	1.44–82.5
Pineapple	170–1627	2.4	0.8–1.6	60–82
Aramide	3000–3150	3.2–3.7	1.4–1.45	63–67
Ramie	400–938	3.6–3.8	1.5	61.4–128
Viscose	593	11.4	–	11
E-glass	2000–3500	2.5	2.5–2.55	73

Table 2 The chemical make-up of plant fibres [4]

Fibre	Lignin(%)	Hemicellulose (%)	Wax (%)	Cellulose (%)	Pectin (%)
Bagasse	22	21	–	37	10
Abaca	12	21	3	62.5	0.8
Banana	7.5	12.5	–	62.5	4
Coir	45	0.3	–	456	4
Alfa	38.5	38.5	2	45.4	–
Cotton	0.75	4	0.6	89	6
Eucalyptus	25.4	32.56	0.22	41.7	8.2
Areca	23–24	13–15.42	0.12	57.35–58.21	–
Hemp	4	20	0.8	81	0.9
Bamboo	26	20.5	–	34.5	–
Hibiscus	22.7	25	–	28	–
Barley	14–19	27–38	2–7	31–45	–
Corn	7–21	28	3.6–7	38–40	–
Cura	7.5	5	–	73.6	–
Flax	2.5	14.5	–	72.5	0.9
Premium	11	30	–	67	–
Henequen	8	28	0.5	60	–
Isora	23	–	1.1	74	–
Ramie	0.8	14	–	72	2
Jute	9	16	0.5	67	0.2
Sisal	8	11.5	–	60	1.2
Kenaf	17	21	–	53.5	2
Wheat	17–19	26–32	6.8	33–38	–
Pineapple	8.3	17.5	–	80.5	4
Rice husk	12–14	23–28	14–20	28–36	–
Sorghum	11	25	–	27	–

Natural fibre bio-composites provide several advantages, including low cost, as well as being more environmentally friendly. Owing to the cutting-edge technology and most advanced processing techniques available today, the applications of natural fibre composites have increased tremendously, ranging in many areas. Bio-composites are used as internal parts of automobiles and in the construction area. As a reinforcing agent, the plant fibres have a replaced conventional reinforcement in numerous applications. Natural fibres are used in surgical and medical applications like medicines, implants, contact lenses, hip joints, wound dressing elements. The automotive industry has implemented natural fibre composites concerning social, environmental, design, and economic responsibilities in almost all their parts. Jute, flax, hemp and coir are the reinforcements used in automotive applications and the packaging industry. Usage of jute, flax, sisal kenaf are reinforcing agents in automotive interior parts such as door, window panels, roofing has been increased. Many automotive companies started to manufacture exterior parts of the vehicles using plant fibres. The construction field uses plant fibres to make degradable door and window panels, railings, fencing elements, false ceilings etc. Many household and office appliances are made from plant fibres; they constitute tables, chairs, food trays, suitcases, pipes, ropes, etc. Before these composites can be exploited to their full potential in the industry, they must enhance their strength and stiffness and address difficulties like water absorption and thermal instability.

5 Future Scope

There is a broad scope for bio-composites in the coming days. There will be increased structural applications. Most of the applications depend on further improvements in processing and enhancing the physical properties. So, a trend in the research can be primarily seen in enhancing the physical properties of the composites. The major challenge with the bio-composites will be adhesion. To improve the bonding between the matrix and reinforcements, new fabrication methods will be incorporated. As fibres are more sensitive to heat and temperature, research might be done in the areas that overcome this issue. Composites exhibit good mechanical properties, but they showed low impact strength and low long-term performance. Many of these flaws will be addressed shortly. Bio-composites will be used to make more robust, more durable, dimensionally more stable, and moisture and fire-resistant. More research is needed to assess the various effects, such as pre-treatment and curing procedures.

There are numerous opportunities for improving the properties in the field of nanotechnology. The field of research includes increased water uptake biodegradation and volatile organic and improving flame resistance. Nanocrystalline cellulose is one compound of focus because it has displayed a more muscular stiffness than aluminium. Nanocrystalline as reinforcement could provide better performance, durability, service life etc. Further research lies in overcoming the weaknesses like moisture absorption, lower strength and low stability. Many researchers are carrying their research in the files of bio-composites to overcome their weaknesses and to have improved performance in engineering applications.

The incorporation of natural fibres in the processing of reliable polymers has been a challenging task. Many research activities have proven natural fibres as a reliable alternative as reinforcement in material science. However, there is much scope for further research in this field to enhance the natural fibre-reinforced composites' physical, thermal and chemical properties. Most research on bio-fibre is untapped, and finding out the undiscovered advantages of bio-fibres is indeed a challenging task.

References

1. Tri-Dung Ngo, Book Chapter: Natural Fibers for Sustainable Bio-Composites, Natural and Artificial Fiber-Reinforced Composites as Renewable Sources, 2018, IntechOpen. (https://www.intechopen.com/chapters/57267)
2. Kozłowski, RyszardMackiewicz-Talarczyk, Maria, Handbook of natural fibres. Volume 2, Processing and applications, 2020, Woodhead publishing
3. Alma Hodzic and Robert Shanks, NaturalFibre Composites Materials, Processes and Properties, 2014, Woodhead publishing
4. M. Ramesh, K. Palanikumar, K. Hemachandra Reddy, Plant fibre-based bio-composites: Sustainable and renewable green materials, Renewable and Sustainable Energy Reviews 79 (2017) 558–584

Trash Pineapple Leaf Fiber Reinforced Polymer Composite Materials for Light Applications

Amberbir Wondimu, Marta Kebede, and Sivaprakasam Palani

Abstract In the modern world, polymeric composites derived from renewable resources, such as biodegradable polymers, are sought out because of their inherent, intrinsic characteristics, such as biodegradability, abundance, environmental friendliness, flexibility, and simplicity in processing. Also, manufactured artificial E-glass fibers are unhealthy and capable of causing cancer, as proven by nature. Natural fibers are due to their natural growth characteristics, making them more accessible to processing and absorption of CO_2. Many researchers concentrate on fibers such as banana, sisal, bamboo, and grass to research alternatives to common natural fibers, including re-grown brush made from grass, which is made into a polymer matrix to degrade naturally and be eco-friendly. Natural fibers (NF) are suitable for producing polymeric composites due to mechanical properties, such as low density, high strength, high flexural modulus, and high impact strength. The present study focused on Pineapple Leaf Fiber (PALF) reinforced polymer composites with a 15% weight percentage. The mechanical properties of PALF reinforced polymer composites are compared with existing synthetic fiber composites. The experimental results show that the PALF reinforced composites having stress ranges of 70–110 kPa; Young's modulus ranges of (4.81–438 kPa). The strain developed in composite material is (11.01–13.29%), and the bending strength of the material is 14 MPa.

Keywords Bio composite · Pineapple leaf fiber · Tensile strength · Strain

---

A. Wondimu (✉)
Department of Mechanical Engineering, Haramaya Institute of Technology, Haramaya University, Harar, Ethiopia

M. Kebede
Department of Mechanical Engineering, Dilla University Institute of Technology, Dilla, Ethiopia

S. Palani
Department of Mechanical Engineering, College of Electrical and Mechanical Engineering, Center of Excellence Nano Technology Addis Ababa Science and Technology University, Addis Ababa, Ethiopia

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_2

1 Introduction

In the technological advancement of human beings and the environment, material engineering plays a primary role. Composite materials are advanced engineering materials that can have limitless application in aerospace, automotive, maritime, civil engineering, electrical, sports, chemical, medical, etc. In reality, composite materials compared to monolithic materials have led to significant cost savings, strength, weight, stiffness, and life span. This is because monolithic materials alone will not have all mentioned characteristics [1]. A composite material is a mixture of two or more materials that are chemically bonded together often with different properties. All of the components' unique features and structure are maintained in the composite. In general, the matrix and reinforcement make up the composite's structure. Continuous and discontinuous phases can be described as being the matrix and reinforcement, respectively. It is the task of reinforcements to obtain the strength of the composite and the matrix to connect the reinforcement. Matrix and reinforcement materials have a familiar interface. However, composite materials typically mix strength, weight, high-temperature efficiency, rigidity, hardness, corrosion resistance, and conductivity that are not possible with the individual components [2].

It is known that there are small and unknown sources of goods dependent on petroleum. So the choice is needed with inexpensive, sustainable and easily accessible raw materials. Plant and fruit-growing countries are not just for agriculture, but also for the supply of industry raw materials. Most developing nations exchange lignocellulosic fibers to improve poor farmers' financial conditions and assist the country. Polymer composites containing cellulosic fibers have recently been concentrated in literature and industries [3]. S. Karthikeyan [4] investigated that composite materials produced by a combination of natural fiber have good mechanical properties, making the majority of researchers pay attention to natural composites for different applications. Mechanical properties of sisal with coir, hemp, and flax fibre-reinforced epoxy hybrid composites are evaluated according to ASTM standards in this work. The research community has paid considerable attention to the development of green and biodegradable materials capable of replacing non-renewable environmental materials [5, 6]. The extensive availability of plant fibers and accessibility are the main reasons given attention to sustainable technology. Emphasis is placed on composite materials due to their lightweight with eco-friendly, highly specialized properties. During this century, the global production of modern natural-resource materials has demonstrated tremendous breakthroughs in green technology [7].

Increased needs for innovative food packaging materials that meet human requirements have given impetus to the advancement of nanomaterial science. The lack of barriers and mechanical qualities of biopolymers has sparked interest in creating innovative techniques to enhance these properties. Research and development of polymeric materials and proper fillers, matrix to filler interactions, and innovative formulation procedures for composites' manufacture may have been used in food packaging [8].

Natural fibers have lower impact and heat stability along with high moisture absorption rate [9]. Natural fibers have a number of limitations that can be remedied via the hybridization approach. The hybridization process was applied by several researchers, who discovered that it had a good influence on thermal and mechanical properties. Two or more NFs are combined into a single matrix to create hybrid composites. Many researchers have attempted to blend two fibers in order to maximize the favorable features of one fiber while minimizing its poor attributes as much as possible. This NF is made up of thin fibers with strong explicit characteristics. Unlike other reinforcing fibers, these are biodegradable and nonabrasive. However, some disadvantages, including as incompatibility with hydrophobic polymer media, and low moisture resistance, significantly limit the potential of NF as polymer reinforcement [10]. However, previous research has shown that chemical treatment approaches, such as surface modification, can improve the nature of the distinctive fibers for more fiber–matrix bonding [11]. NFC also has enticing environmental and economic views, as well as the ability to deal with human difficulties. Green fiber composites have significant potential in the aerospace and automotive industries [12]. Plant-based NF, a high-potential field for PMCs material, has lower density, important material features and outstanding flexibility in forming due to lightweight and cost effective products. Increased consumer demand for green technologies with increased mechanical performance and functionality has been attracted by the use of plant fibers in the core structure of composite materials. Fiber-based composites are widely used for their superior characteristics in the building, automotive, packaging, sport, biomedicine and defense sectors [13].

V. P. Wambua [14] studied the reinforced polypropylene composites of NF (jute, kenaf, hemp, sisal, and coir) manufactured by compression molding using a film stacking techniques. The mechanical properties of the various NFCs have been checked and compared. A comparison was also performed with the parameters of glass-reinforced polypropylene composites published in the various literatures. In most cases, the specific properties of NFC have been favourably compared with glass. W. Wang [15], studied moisture absorption of composites. This investigation discovered that accessible fiber ratio and coefficient of diffusion permeability were represented; the percolation model built was to calculate the critically accessible fiber ratio; and finally, different fiber load composite moisture absorption and electrical conductivity were evaluated.

K. Palani Kumar et al. [16] analyzed mechanical properties of artificial fiber (glass fiber), and natural fiber (sisal) reinforced composite using the hand layup method. The prepared sample has been subjected to various testing to evaluate mechanical properties. The study shows that hybridization of two fibers has considerable enhancement in the mechanical properties and reduces effects on the ecosystem. The internal structure of fractured surface failure morphology and delamination of fiber has analyzed with ultramicroscopic analysis. M. Harikishnan et al. [17] performed mechanical properties analysis of hybrid composite with three different fiber materials such as glass, jute, and banana fiber. The findings reveal that a jute-banana-glass fiber reinforced hybrid composite has outstanding qualities and can be utilized as a substitute for composites with artificial fiber reinforcement.

Vikas Kumar et al. [18] conducted mechanical properties analysis of hybrid composite (jute-glass fiber with epoxy resin). The experiment is done with TiO_2 as a filler material. The different weight percentage of filler material is 0%, 4% and 8%. The result shows the jute-glass fiber hybrid composite with 8% filler material has maximum tensile strength, and 4% filler material has the ultimate bending strength. Suresha K.V [19] conducted a study on hybrid composite is made with hemp fiber and the artificial fibers used are glass fiber and carbon fiber. The fabricated hybrid composite material has hemp/glass/epoxy and hemp/carbon /epoxy with the same thickness of 3 mm through the hand layup technique. The prepared sandwich panels were tested tensile compressive and flexural test.

Sunita. R et al. [20] studied the natural fibre-based composite with epoxy as matrix material with horsehair and human hair as reinforcement materials. The test result shows that the hybrid composite has better properties than each composite material like human hair and epoxy or horsehair and epoxy. The different natural fiber is used, and their mechanical and chemical properties compare to each other [21]. The mechanical behaviours of glass fibers are also compared to natural fiber. The study of mechanical property of natural fiber depends on the loading condition of the material and weight percentage of fiber. Siva I [22] investigated coconut sheath reinforcement in unsaturated polyester (general purpose grade). The results show that the fiber volume fraction increases the flexural strength and hardness values, while impact strength has reduced.

Investigation on natural fibre-based hybrid composite was performed by A. A Nair [23]. The fibers used in this work are animal fiber (human hair) and plant fiber (coir). The prepared three samples are pure coir fiber-based composite and coir/human hair hybrid composite material. The flexural, tensile, compressive and impact strength of composite materials were investigated. The result shows the investigated composite material that is coir/ hair hybrid has better properties. Somashekar S.M et al. [24] Developed glass and hemp fiber reinforced hybrid polymer composite. The artificial fiber use is bi-directional, and the natural fiber is untreated. The mechanical test of the composite is carried out with different fiber orientation. The test result shows that natural fiber composite has better performance than glass fiber. The hybridization of composites using jute and sisal fabrics reinforcement in epoxy by hand layup method was investigated by Pereira A.L et al. [25]. The toughness of sisal + curauá (S + C) and jute + curauá (J + C) components have been found to increase through hybridization (pure sisal and jute fabrics) due to hybridization of intralaminar has limited crack propagation.

S. Suresh et al. [26] have investigated the cost-effective use of agricultural residues by reinforcing coconut shell, rice husk and bagasse in PMCs. The weight proportion of reinforcement particles in the composite material range (5–25 wt %) and their effects on wear properties, water absorption and mechanical performance were analyzed. The SEM shows that the inclusion of coconut shell, bagasse, and rice husk particles improved mechanical and tribological characteristics. Hot-pressing was used to create multi-layered hybrid composite films, and their performance in electromagnetic interference shielding was investigated [27]. With the inclusion of jute, the composites' shielding efficiency dropped. However, the wear properties of composites improved with increasing jute content until it reached an optimal value of 10% wt. After that, it began to deteriorate [27].

The superior mechanical and thermic properties of composite could be enhanced through; PALF and Coir Fibers (CF) were mixed into a polylactic acid (PLA) matrix that might be used as biologically degradable food packaging. Bio-composites were produced using and a hot-press machine with different fiber ratios. Mechanical and thermal analysis was performed, and the results compared [28]. SEM observed the micro structural failure of the composites. All of the composites had higher tensile and bending modules than pure PLA. In addition, strength values were increased when PALF was added, while impact tests showed improved strength results when CF was added. Dynamic mechanical analysis results confirmed that the CF/PALF/PLA hybrid composite storage and loss module increased in relation to those of the clean PLA, while the temperature declined. The added fiber reinforcement's leads to a coefficient of thermal expansion decreased in PLA composites. The findings demonstrate that hybrid composites comprising CF and PALF in a 1/2 ratio (C1P1) are ideal mechanical properties and increased thermal stability, making them appropriate for applications in packaging and structural components [28].

Abir Saha et al. [29] examined the thermomechanical characteristics of PALF reinforced PMCs with under the influence of micro-particular pineapple inclusion. Constant weight fractions of PALF (30%) and five-level weight fractions (2.5–10%) of particulates are taken to develop hybrid composites. The study includes microparticle preparation, chemical processing (with a 5% NaOH solution) and microparticle characterization. The results show that particulate processing has better thermal stability and crystalline structure, which will improve mechanical and thermal features of composites. Chemically treated particles were added to PALF reinforced composites has enhancement in interfacial adhesion between the matrix and the fibers will helps improvements in composites, especially thermal and mechanical properties. According to the findings, 7.5% of the particle addition has the best hardness, tensile, compressive, and flexural properties and better plane strain fracture toughness. Water absorption and biodegradability test also revealed that better water absorption and biodegradability in the addition of particulates. The SEM was applied to study morphological behavior with particulate wt% and also analyze the composites fracture behavior.

The hybridization improved the composites' mechanical characteristics and moisture absorption behaviors [30]. The mechanical properties of hybrid composites (kenaf–PALF) confirmed that 10.90%, 16.13%, 6.80% improvements in tensile, flexural and impact strength, respectively. In addition to that diffusion coefficient of materials was reduced to 56.12%. The hybridization of composites could help balance the moisture sensitivity and mechanical properties. The mechanical characteristics of a PALF–based short fiber reinforced polymer composite were investigated by Jagadish et al. [31]. Addition of short fibers, capable of improving mechanical properties and improving their performance in every process composites of 10 percent strengthening + 5 mm thickness than other combinations [31]. An impact on the mechanical properties of PALF reinforced-epoxy composites was examined by the length and content of the fiber [32]. In this case, four composite samples were generated utilizing a hand lay-up method with four fiber length various 10 mm to 20 mm; fiber content of 17, 23, 34, and 43 vol. %. The composite tensile and flexural strength was enhanced by 34 vol%, at 15 mm and 25 mm, 43 vol. % content has the highest impact strength [32]. According to this study, the 60/40 wt% with 30 mm fiber length of manufactured with ideal compression molding conditions is the most excellent combination for obtaining a high tensile strength value. The tensile strength fell by only 1.9 percent when compared to the projected value [33].

A unique approach for extracting PALF has been presented by Nanthaya Kengkhetkit [34]. The extraction process enables the production of short and fine PALF. With a cut length of 6 mm and a diameter of 3 µm, the aspect ratio of this PALF may be up to 2000 (length to diameter ratio). These properties make this PALF an excellent choice for effective plastic and rubber reinforcing. It will be demonstrated how to use this PALF to its full potential. This PALF could, as with other cellulose fibers, be treated or used with a compatible or adhesion promoter on the surface. Recent advancements will be discussed, as well as possible applications.

Ng Lin Feng et al. [35] performed a thermal compression process to manufacture Kenaf and PALF-based composites. The results show that chemical treatments increased composite materials properties. The best mechanical characteristics for kenaf fiber and reinforced composites can be provided by 5% of NaOH and 3% silane treatments. The results of chemical therapy have shown that composites treated with silane have greater mechanical qualities than composites treated with NaOH. When comparing kenaf- and PALF-reinforced polypropylene composites with its mechanical characteristics, the overall results suggest that PALF composites have higher mechanical characteristics.

To summarize the above-related literature, numerous researchers have done a great job on composite materials as a general. However, excellent work on natural composites is still being done due to the abundance of species addressed only by plant researchers. This research will fill knowledge gaps and study such a new source of materials for light mechanical applications.

2 Materials and Methods

2.1 Fiber Extraction

The fiber was extracted from pineapple leaf through hand scraping technique, rinsed in distilled water, and dried in the sun for 1 h. The second step has to be pineapple fiber mercerization. It has a process of treating pineapple fiber after oven with 10wt% Na OH solution at room temperature for 24 h. Next, the fiber has rinsed with water to remove the soda excess until PH~7 will reach. Finally, the fiber has been dried by sunlight which is shown in Fig. 1.

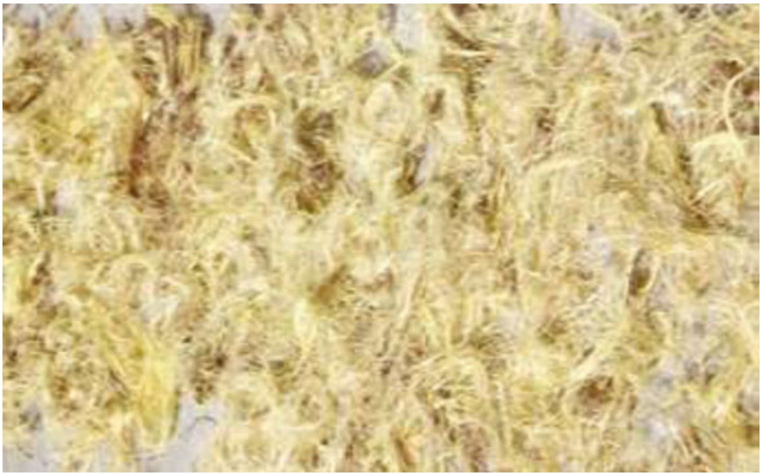


Fig. 1 Dry Pineapple fiber

2.2 Epoxy and Hardener

The commercially available epoxy [OCPOL-711 N] resin has mixed with hardener 2060. The blending of epoxy and hardener weight ratio 10:1 was used. Anhydrides, polyamides, dicyandiamide, and other hardeners are among them. The mixing is done in the containers. Although the bowl melting could be avoided during the process with the tongue depressor, the bowl is prepared with nickel; the combination is done carefully to avoid inducing any surplus air bubbles in the resin.

2.3 Hand Lay-Up Method

The mold has been filled with an adequate amount of epoxy resin mixture and layers of pine-apple fibers (random), starting and ending with resin layers, using the hand-lay-up method (Fig. 2). At room temperature, the amount of accelerator and catalyst added to the resin was 1% by volume of resin. To generate high-quality random fiber composites, fiber deformation and movement should be reduced. The mold was subjected to a compression pressure of 50 bar (5 MPa) during the curing process. The hydraulic press was used to gently press out the air gaps generated by the fibers, forcing the air between the fibers and the resin, which is held for several hours in order to produce excellent samples. Wet composite was then pressed hard and excess resin removed and dried. The final prepared composites with 15% PALF and 85% epoxy shown in Fig. 3.

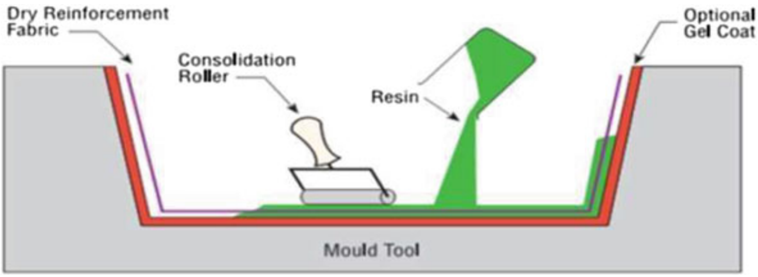


Fig. 2 Hand layup [36]

Fig. 3 Prepared composites [15% fiber to 85% epoxy]

2.4 Mold Release

The release of the mold is essential to prevent the epoxy from sticking to the mold when the composite is separate. Although several types of mold releases are used depending on the mold material and the desired characteristics of the finished part, the most common type used for this work is paste wax and aluminium foil for better surface finishing of the composite. The composite is dried within 2–3 h in which the fibers of the pineapple and the polymers adhere tightly in the presence of a hardener.

Fig. 4 Test specimens with ASTM D 3039 Standard

2.5 Experimental Test Setups

The experimental setup used for tensile, compression and bending testing is a universal testing machine (UTM) shown in Fig. 5a–c correspondingly. The length, width and thickness of the specimen were 250 × 25 × 5 mm given in Fig. 4. The tensile test was performed as per ASTM standard, and the maximum machine loading capacity was 50KN, but for each sample, it will not exceed such limit and all acting loads are below such limits as shown in experiments. The test result shows very good agreement with relevant literature. A compression test has performed to characterize the compression strength of the PALF- epoxy composite for three test samples prepared as per ASTM D3410 standard. The three-point bending test has performed with maximum acting load for composite is 50KN, which have a standard size of the specimen to be tested is length 250 mm, width 25 mm and thickness 5 mm, were tested.

3 Results and Discussion

3.1 PALF Reinforced Composites—Tensile Test

The mechanical properties of PALF reinforced composites (tensile, compression strength, and maximum strain) have been presented and discussed. Many variables, such as fiber content and length, influence the mechanical properties of the composite. The tensile test was performed as per ASTM 3039 standard using a UTM. The load applied for such a case was 50 KN, and the specimen size was 250 mm, 25 mm width, 5 mm thickness, and the test result shows very good agreement with relevant literature.

Figure 6, Shows the tension test result of pineapple leaf fiber reinforced epoxy composite stress versus strain curve of test; as stress increases, the corresponding strain increases until the ultimate stress (100 kPa) of the specimen, then failure will happen beyond this limit. All the three test specimens are similar fashion, and the comparative results of stress and strain curve shown in Fig. 7.

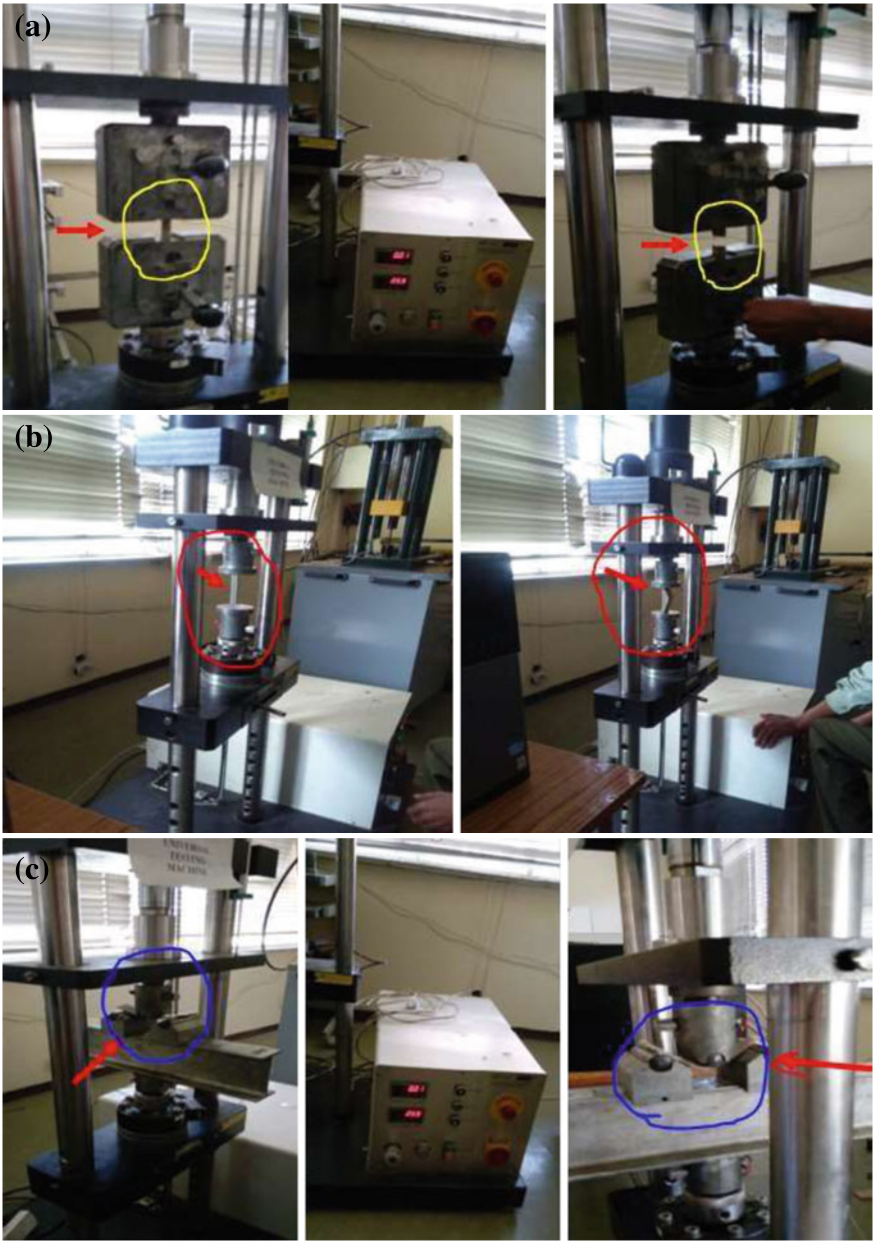


Fig. 5 **a** UTM—tensile test. **b** UTM—Compression Test **c** UTM – Bending test

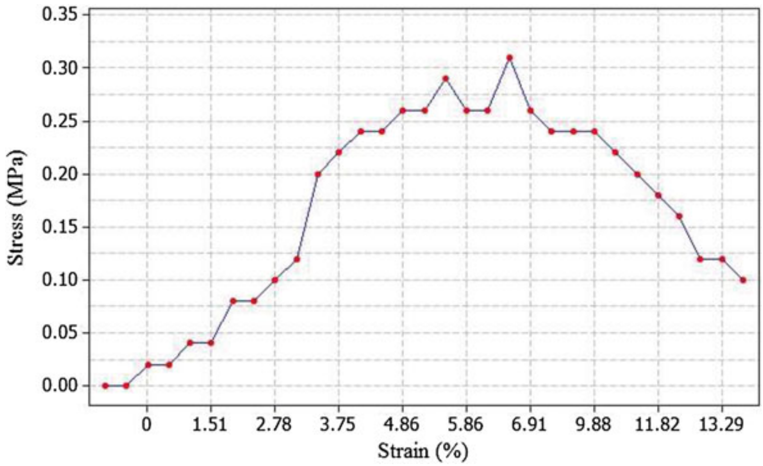


Fig. 6 Stress–strain curve tensile test [sample 1]

Experiments were carried out on three specimens, each prepared as per ASTM standards, and their strain, tensile strength, and young's modulus values were presented in Table 1. Tensile strength for ASTM D-3039 possesses a standard deviation of 10, which mean that the observed in Table 1 tensile strength values disperse from the mean value at a smaller range. Conversely, in the case of young's modulus standard deviation value is very small (1.156), which indicates that the data points tend to be very close to the mean Young's modulus values.

Figure 7 curve sample 1 shows the tension test result of pineapple leaf fiber epoxy composite load versus deformation curve of test sample 1. The curve clearly shows as the load increases, the corresponding deformation increases until the maximum deformation (6.53 mm) of the specimen, which means beyond such limit, failure will happen on the material. In addition to that, similar observation has found sample 2 and sample 3, the deformation values 6.27 mm and 6.42 mm, respectively. Table 2 shows that the comparison of test samples axial load versus deformations.

.

Table 1 Pineapple Leaf fiber reinforced composite tensile test result

Specimen no	ASTM standards	Strain (%)	Tensile stress (KPa)	Young's modulus (KPa)
ST-1	ASTM D3039	13.29	100	438
ST-2	ASTM D3039	14.62	90	436
ST-3	ASTM D3039	15.13	110	438
	Mean	14.342	100	437.3
	Standard deviations	0.949	10	1.156

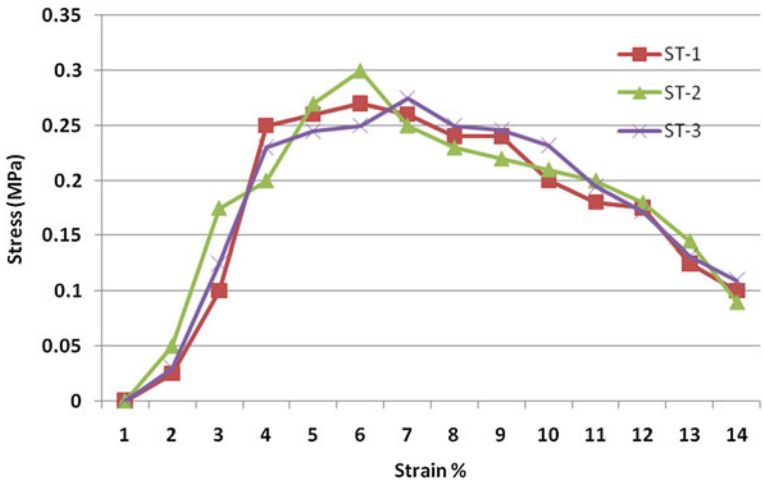


Fig. 7 Pineapple leaf fiber reinforced composites tensile test [Stress–Strain curve]

Table 2 Pineapple leaf fiber tensile test result for load–deformation curve

Specimen No	ASTM Standard	Deformation (mm)	Axial Load (N)
ST-1	ASTM D3039	6.53	50
ST-2	ASTM D3039	6.27	45
ST-3	ASTM D3039	6.42	48
	Mean	6.40	46.77
	Standard Deviations	0.1350	2.51

3.2 Pineapple Leaf Fiber Reinforced Composites—Compression Test

The compression test is done to characterize the compression strength of the PALF-epoxy composite for three test samples prepared based on ASTM 3410 standard with length 155 mm, width 25 mm and thickness 5 mm.

Figure 8 shows that compression stress versus strain plot of pineapple leaf fiber reinforced composite subjected to compression load in universal compression testing machine. Stress versus strain will continue until the material gets its ultimate stress of 100 kPa. The comparative results of the other two test specimens exhibit similar results presented in Table 3.

Figure 9 shows that compression test result of pineapple leaf fiber reinforced epoxy composite load versus deformation curve of test sample number 1. The curve clearly shows as the load increases, the corresponding deformation increases until the maximum deformation (6.53 mm) of the specimen, which means beyond such

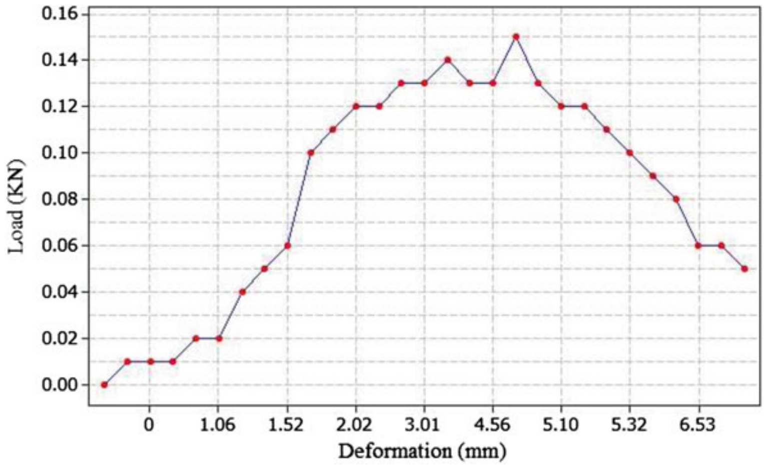


Fig. 8 Load-deformation curve sample 1

Table 3 Pineapple leaf fiber reinforced composites—compression test result

Specimen No	ASTM standards	Strain (%)	Compression stress (KPa)	Young's modulus (KPa)
ST-1	ASTM D3410	13.29	100	8.14
ST-2	ASTM D3410	12.29	95	7.52
ST-3	ASTM D3410	11.99	98	8.56
	Mean	12.52	97.67	8.07
	Standard Deviations	0.680	2.51	0.5232

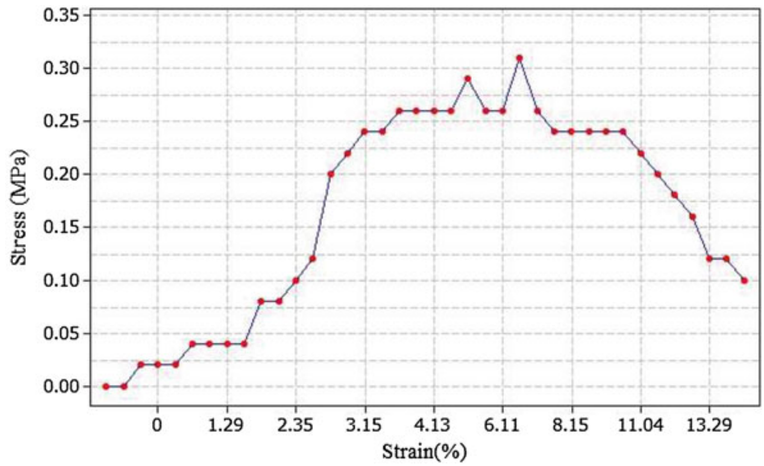


Fig. 9 Compression test–stress–strain curve [sample 1]

Table 4 Pineapple leaf fiber reinforced composites—compression test [Load–Deformation]

Specimen No	ASTM Standards	Deformation	Load (N)
ST -1	ASTM D3410	6.53	50
ST -2	ASTM D3410	5.53	52
ST -3	ASTM D3410	7.56	47
	Mean	6.54	49.66
	Standard Deviations	1.015	2.517

limit, failure will happen on the material. Table 4 shows the comparative test results of the other two samples. The maximum deformation has been taken for sample 2 and 3 were 5.53 mm and 7.56 mm, respectively.

3.3 Pineapple Leaf Fiber Reinforced Composites—Bending Test

Figure 10 shows the three-point bending test has a maximum acting load for composite is 50KN, which have a standard size of the specimen to be tested is length 250 mm, width 25 mm and thickness 5 mm, were tested. The bending stress in MPa and loads in Newton's are summarized in Table 5, which shows all results are read from the computer attached with UTM. At the same time, each test is done below the standard in which the UTM machine can work for composite materials; these are recommended values for the test specimens.

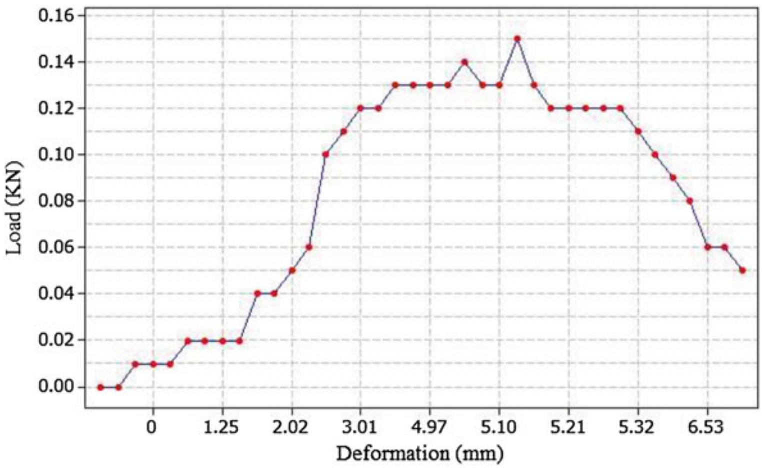


Fig. 10 Load–deformation curve for compression test [sample 1]

Table 5 Pineapple leaf fiber reinforced composites - bending test

Specimen No	ASTM Standards	Bending Stress (N/mm^2)	Max Load (N)
ST-1	ASTM D 7264	12	55
ST-2	ASTM D 7264	16	50
ST-3	ASTM D 7264	14	60
	Mean	14	55
	Standard deviations	2.0	5

3.4 Comparison of Mechanical Properties

As shown in Fig. 10, a comparison of the experimental result obtained through this research is compared with relevant literature. The properties obtained for pineapple leaf fiber reinforced epoxy composite was comparable properties with other natural and synthetic fiber epoxy composites.

Figure shows those comparative results of PALF reinforced epoxy composite with existing literature [1, 15, 37]. Figure 11 shows that pineapple fiber epoxy composite has comparable with relevant literature discussed on [1, 15, 37]. Hence elongation of both pineapple leaf fiber reinforced epoxy composite have comparable elongation and strain with existing relevant literature. Therefore, it is better to use light mechanical applications like packaging and bottling instead of synthetic fiber for such applications.

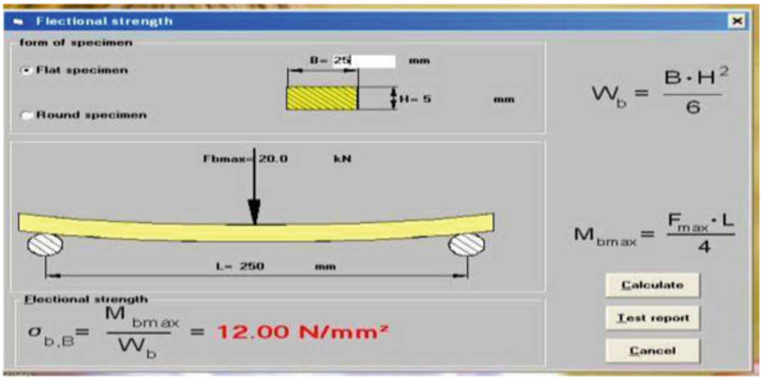


Fig. 11 Bending strength of sample 1

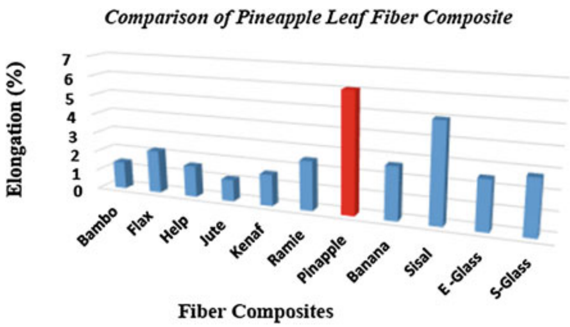


Fig. 12 Comparition of fiber reinforced composites with pineapple leaf fiber

4 Conclusions

This experimental investigation to mechanical behavior of PALF reinforced epoxy composites indicates the fiber have comparable strengths to substitute the glass fiber epoxy composites which have strong environmental influence and cost. Therefore, the following points are concluded finding of the research work: -

- Pineapple leaf fiber reinforced epoxy composite has better strength as compared to other fiber reinforced epoxy composite and it has comparable strength with E Glass and other fiber source.
- The tensile stress of PALF reinforced epoxy composite material has in the ranges of 70–110 kPa
- Young's modulus of PALF reinforced epoxy composite was 4.81-438 kPa.
- Strain of the material developed was 11.01–13.29% - Bending strength of the material was 14 MPa.

References

1. Wang RM, Zheng SR, Zheng YP (2016) Polymer matrix composites and technology, Published 2016, Woodhead Publishing, ISBN-10: 0–08–101724–3
2. Vasiliev VV, Morozov EV (2013) Chapter 1 - Introduction, Advanced mechanics of composite materials, (Third Edition), Elsevier, pp 1–27, ISBN 9780080982311
3. Razali N, Salit MS, Jawaid M, Ishak MR, Lazim Y (2015) A Study on Chemical Composition. Physical, Tensile, Morphological, and Thermal Properties of Roselle Fibre, bioresources 10(1):1803–1824
4. Karthikeyan S, Rajini N, Jawaid M, Winowin Jappes JT, Thariq MTH, Suchart Siengchin J, Sukumaran, (2017) A review on tribological properties of natural fiber based sustainable hybrid composite. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 231(12):1616–1634
5. Ojha S, Raghavendra G, Acharya SK (2014) A Comparative Investigation of Bio Waste Filler (Wood Apple-Coconut) Reinforced Polymer Composites. Polym Compos 35:180–185
6. Molaba TP, Chapple S, John MJ (2016) Aging Studies on Flame Retardant Treated Lignocellulosic Fibers. J Appl Polym Sci 133(44):44175

7. Ramesh M, Palanikumar K, Reddy KH (2017) Plant fibre based bio-composites: Sustainable and renewable green materials. Renew Sustain Energy Rev 79:558–584
8. Majeed K, Jawaid M, Hassan A, Abu Bakar A, Abdul Khalil HPS, Salema AA, Inuwa I (2013) Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites. Mater Des 46:391–410
9. Faruk AK, Bledzki HP, Sain FM (2012) Biocomposites reinforced with natural fibers. Prog Polym Sci 37(11):1552–1596
10. Jacob M, Francis B, Thomas S, Varughese KT (2006) Dynamical Mechanical Analysis of Sisal/Oil Palm Hybrid Fiber-Reinforced Natural Rubber Composites. Polym Compos 27(6):671–680
11. Furqan A, Choi HS, Park MK (2014) Natural fiber composites selection in view of mechanical, light weight, and economic properties. Macromol Mater Eng 300:10–24
12. Saheb DN, Jog JP (1999) Natural fiber polymer composites: a review. Adv Polym Technol 18(4):351–363
13. Mahmud S, Hasan KMF, Jahid MA (2021) Comprehensive review on plant fiber-reinforced polymeric biocomposites. J Mater Sci 56:7231–7264
14. Wambua P, Ivens J, Verpoest I (2003) Natural fibres: can they replace glass in fibre reinforced plastics. Compos Sci Technol 63(9):1259–1264
15. Wang W, Sain M, Cooper PA (2006) Study of moisture absorption in natural fiber plastic composites. Compos Sci Technol 66(3–4):379–386
16. Palanikumar K, Ramesh M, Hemachandra Reddy K (2016) Experimental investigation on the mechanical properties of green hybrid sisal and glass fiber reinforced polymer composites. Journal of Natural Fibers 13(3):321–331
17. Harikrishna M, Ajeeth K, Ranganatha S, Thiagarajan C (2018) Fabrication and Mechanical Properties of Hybrid Natural Fiber Composites (Jute/Banana/Glass). International Journal of Pure and Applied Mathematics 119(15):685–696
18. Kumar V, Mashetty S (2019) Mechanical Characteristics of Jute-Glass Fiber Reinforced Composite. International Research Journal of Engineering and Technology 6(4):1143–1146
19. Suresha KV, Sumana BG, Shivanand HK, Mahesha, (2017) Tensile, Compression and Flexural Behavior of Hybrid Fiber (Hemp, Glass, Carbon) Reinforced Composites. International Journal of Engineering Development and Research 5(4):688–698
20. Rasbhar S, Alam S, Stivastava R (2016) Fabrication and characterization of animal hair and human hair rein-forced epoxy composite. International Journal and Scientific Processes and Application 2(2):18–22
21. Srinivas K, Lakshumu Naidu A, Raju Bahubalendruni MVA (2017) A Review on Chemical and Mechanical Properties of Natural Fiber Reinforced Polymer Composites. International Journal of Performability Engineering 13(2):189–200
22. Siva I, Winowlin Jappes JT, Sankar I, Amico SC, Ravindran D (2013) Effect of Fiber Volume Fraction on the Mechanical Properties of Coconut Sheath/Usp Composite. Journal of Manufacturing Engineering 8(1):60–63
23. Nair AA, Prakash S, Paul DRC (2017) Synthesis and Characterization of Hybrid Polymer Composites. International Journal of Advanced Engineering Research and Science 4(3):23–28
24. Somashekar SM, Manjunath V, Gowtham MJ, Balasubramaniam NS (2016) Investigation on mechanical properties of Hemp-E glass fiber reinforced polymer composites. International Journal of Mechanical Engineering and Technology 7(3):182–192
25. Pereira AL, Banea MD, Pereira AB (2020) Effect of intralaminar hybridization on mode I fracture toughness of natural fiber-reinforced composites. J Braz Soc Mech Sci Eng 42:451
26. Suresh S, Sudhakara D, Vinod B (2020) Investigation on Industrial Waste Eco-Friendly Natural Fiber-Reinforced Polymer Composites. Journal of Bio- and Tribo-Corrosion 6(40):1–14
27. Joseph J, Munda PR, Kumar M, Sidpara AM, Paul J (2020) Sustainable conducting polymer composites: study of mechanical and tribological properties of natural fiber reinforced PVA composites with carbon nanofillers. Polymer-Plastics Technology and Materials 59(10):1088–1099

28. Siakeng R, Jawaid M, Ariffin H, Sapuan SM (2018) Mechanical, Dynamic, and Thermomechanical Properties of Coir/Pineapple Leaf Fiber Reinforced Polylactic Acid Hybrid Biocomposites. Polym Compos 40(5):2000–2011
29. Saha A, Kumar S, Kumar A (2021) Influence of pineapple leaf particulate on mechanical, thermal and biodegradation characteristics of pineapple leaf fiber reinforced polymer composite. J Polym Res 28:66
30. Feng NL, Malingam SD, Ping CW, Razali N (2020) Mechanical properties and water absorption of kenaf/ pineapple leaf fiber-reinforced polypropylene hybrid composites. Polym Compos 41(4):1255–1264
31. Jagadish, Rajakumaran, M, Ray A (2018), Investigation on mechanical properties of pineapple leaf–based short fiber–reinforced polymer composite from selected Indian (northeastern part) cultivars, Journal of Thermoplastic Composite Materials, 1–19.
32. Mittal M, Chaudhary R (2021) Effect of Fiber Length and Content on the Mechanical Properties of Pineapple Leaf Fiber Reinforced-Epoxy Composites. Advances in Science and Technology 106:68–77
33. Selamat M.Z, Kasim A.N, Malingam S.D, Daud M.A.M. (2020), Optimization of Compression Molding Parameters for Pineapple Leaf Fiber Reinforced Polypropylene Composites Using Taguchi Method. In: Sabino U., Imaduddin F., Prabowo A. (eds) Proceedings of the 6th International Conference and Exhibition on Sustainable Energy and Advanced Materials. Lecture Notes in Mechanical Engineering. Springer, Singapore.
34. Kengkhetkit N, Wongpreedee T, Amornsakchai T (2018), Pineapple Leaf Fiber: From Waste to High-Performance Green Reinforcement for Plastics and Rubbers. In: Kalia S. (eds) Lignocellulosic Composite Materials. Springer Series on Polymer and Composite Materials. Springer, Cham. 271–291.
35. Feng NL, Malingam SD, Razali N (2020) Alkali and Silane Treatments towards Exemplary Mechanical Properties of Kenaf and Pineapple Leaf Fibre-reinforced Composites. J Bionic Eng 17:380–392
36. Udupi SR, Rodrigues LLR (2016) Detecting Safety Zone Drill Process Parameters for Uncoated HSS Twist Drill in Machining GFRP Composites by Integrating Wear Rate and Wear Transition Mapping. Indian Journal of Materials Science, Article ID 9380583:1–8
37. Ibrahim ID, Jamiru T, Sadiku ER, Kupolati WK, Stephen C, Agwuncha GE (2016) Mechanical properties of sisal fibre-reinforced polymer composites: a review. Compos Interfaces 23(1):15–36

Bio-fibre Reinforced Polymeric Composites for Industrial, Medicine and Domestic Applications

R. Vinayagamoorthy

Abstract Polymer based composites are nowadays in high demand due to customized characteristics during its processing stage. In order to increase the bio-degradability, polymeric composites are mostly incorporated with bio-fibres and sometimes with both bio-fibres and artificial fibres in hybrid form. Many researches have been attempted to prove that bio-fibres are on par with the artificial fibres in terms of strengths and most of the researches have explored it successfully. Several researches have been made in the last decade to study the characters of the bio-fibre composites and few on the applications of such composites in different fields. Hence, the present survey has been aimed to explore the applications of composites made from bio-fibres, artificial fibres and under a combination of both in major areas. This survey also show a vivid view on difficulties encountered during composite preparation, suitability of the prepared composite and a comparative analysis on its characters with the conventional materials for a specific application.

Keywords Applications · Bio-fibres · Hybrid composites · Characters · Bio-degradability

1 Introduction

Bio-fibre based composite materials are prepared by using naturalreinforcements such as plant fibres, animal fibres, mineral fibres etc. They are well proven to be the best against the materials made of artificial reinforcements such as glass, kevlar and carbon [1, 2]. Bio-fibres are broadly classified in to three types namely, anima fibres, mineral fibres and plant fibres. Animal fibres are derived from the animal wastages such as bones, furs, intestines, feathers of birds etc. Mineral are natural sources obtained from the underground, sediments and from rocks such as asbestos, basalt, soil, clay, gold, silver, talc, calcite, granite, limestone, marble etc. Plant fibres are

R. Vinayagamoorthy (✉)
Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya, Department of Mechanical Engineering, Kancheepuram-631561, India
e-mail: vin802002@gmail.com

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_3

extracted from different parts of the plant when they are destructed [3]. Fibres derived from the stem are known to be bast fibres like flax, kenaf, bamboo, ramie, jute etc. Fibres obtained from fruit include coir, husk, luffa etc. and fibres obtained from fruit seeds include cotton, kapok, milkweed, linseed. Plant fibres are also obtained from leaf which includes abacca, banana, henequen, pineapple etc. and fibres obtained from plant roots includes vetiver, maize, marvel grass, bermuda grass etc. Apart from these parts of the plants, several grasses have been used as fibres which include rice, barley, corn, wheat, etc. [4, 5].

Pristine bio-fibres are not generally used as it possesses impurities and unwanted substances hence; bio-fibres are to be synthesized before it is used as reinforcement in composite material. This synthesis enhances the strength and other characters of the fibre and thus elevates the characters of the entire material [6–8]. Due to the increased usage of bio-fibres, they are produced commercially round the year. The annual production of some common bio-fibres along with their important characteristics is presented in Table 1. Bio-fibre based composites are used by almost all countries around the globe. The major users are presented in Fig. 1. China being the leading user of bio-fibres followed by India, USA, South Korea and Germany [9].

Applications of bio-fibre composites are wide. They produce commendable characteristics such as high mechanical strengths to weight ratio, wear properties, water absorption, sound and electrical characteristics. Bio-fibre composites find its place in almost all industries like structural components in aircrafts, automobiles, ships, electrical and electronic appliances, household utensils, structural elements in construction industry, replacement for human organs in medical field etc. They present survey gives a comprehensive and avivid overview of various applications of bio-fibre composites in major areas, their success, suitability and superiority in comparison with the conventional materials and the reasons behind each phenomenon.

Table 1 Bio-fibre production in the world [10–13]

S. No	Bio-fibres	Production (Tons)	Density (g/cm^3)	Tensile strength (MPa)	Young's Modulus (GPa)	Strain at break (%)
1	Abaca	70,000	1.5	980	–	–
2	Ramie	100,000	1.5	500	44	2
3	Coir	100,000	1.25	220	6	15–25
4	Hemp	214,000	1.48	550–900	70	1.6
5	Sisal	375,000	1.33	600–700	38	2–3
6	Flax	830,000	1.4	88–1500	60–80	1.2–1.6
7	Kenaf	970,000	1.2	295	–	2.7–6.9
8	Jute	2,300,000	1.46	400–800	10–30	1.8
9	Bagasse	75,000,000	1.2	20–290	19–27	1.1
10	Bamboo	30,000,000	1.2	441	36	1.3

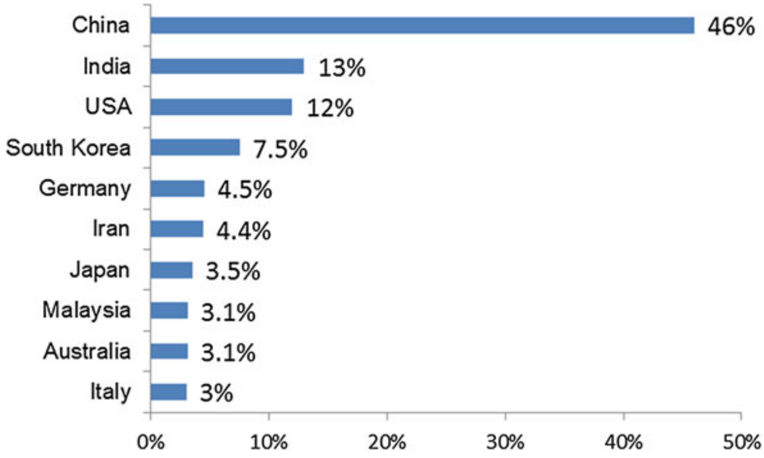


Fig. 1 Bio-fibre users around the globe

2 Automotive Applications

Bio-fibre reinforced plastics have been mostly used as structural items in automotive parts by major automobile manufacturers. The inner parts such as dashboard and partitions of E-class cars are made up of bio-composites. The inner trim panels of car door are made up of composite with 60% bio-fibre and 40% polyurethane matrix [14, 15]. Kenaf on the other hand used along with glass as a sandwich composite produced impeccable mechanical properties and makes it ideal for bumper beams in cars [16]. Flax fibre reinforced plastics produced high coefficient of friction at low wear rate during friction characterization and hence they are desirable for brakes lining and brake pad in automobiles [17, 18]. Sound absorption is another important phenomenon that helps a material to be suitable for sound boxes inside the cars and the interior walls of the auditorium. Three natural fibres namely banana, bamboo and jute have been reinforced in to the polypropylene matrix in the form of composites. A detailed study on the mechanical and sound absorption has been conducted and it has been divulged that, bamboo reinforced composites have exhibited outstanding mechanical strengths and highest sound absorption. Next to bamboo, jute also provides notable sound absorption whereas banana reinforced composites showed a scanty sound absorption of 22% lesser than others [19].

Sisal fibres have been reinforced in epoxy matrix during the development of bio-composites. An all-inclusive study on its characters has been made and recorded a maximum tensile strength of 55 MPa, flexural strength of 86 MPa and impact strength of 0.6 J/mm^2. The composite has been developed in the form of mud guard and bumpers for two wheelers and proclaimed that, sisal is lofty in strength as compared to that of the conventional glass. In addition, the composite is found to be consummate in cost reduction and weight saving [20, 21]. Like this, many interior parts of an automobile are made up of bio-fibre composites. Some important parts are shown in

Fig. 2. Disparate researches have been made in last decade to examine the behaviour of bio-fibre composites as automotive parts. Some of them are listed in Table 2.

Fig. 2 Bio-fibre composites for various parts automobiles

Table 2 Applications of bio-composites in automotive industry

S. No	Fibres/Matrix	Application	References
1	Jute and glass/polyester	Seat backings, bumpers, luggage shelves in cars	[22]
2	Jute/polyester	Body panels of prototype cars	[23, 24]
3	Hemp and flax/polypropylene and polyester	Floor-well panels in cars	[25]
4	Coconut/ rubber latex, Flax and sisal/ epoxy	Seats and door panels in in Mercedes Benz-A and E model cars	[26]
5	Flax and sisal mat/polyurethane	Door trim panels in Audi cars	[27, 28]
6	Kenaf and flax/polypropylene	Door panels and floor trays in Ford cars	[29]
7	Flax/polypropylene	Rear shelf trim panels in Chevrolet cars	[30]
8	Roselle, banana and sisal/epoxy	Visor, side cover, indicator cover, billion sear cover in two wheelers	[31, 32]
9	Flax / Polyester	High roof of cars	[33]
10	Coconut/rubber	Seat bottoms, heat restraints, inner trim, backrests	[34, 35]
11	Recycled fibrowood/polypropylene	Retainer for seat back panel	[36]
12	Cotton/polypropylene	Sound proofing, insulations, trunk panel	[37, 38]
13	Wood flour/polypropylene or polyolefin	Carrier for door panels, arm rest and covered inserts	[39]
14	Wool/leather	Seat covers and upholstery	[40]
15	Bamboo/polyurethane	Door panels	[41, 42]

3 Aerospace Industry

It has been recorded that, almost 50% of the parts of an aeroplane are made from composite materials. The primary objective of using such materials is the optimum strength to weight ratio. Flyer-1 made by Wright Brothers is the first one to use wood and natural fabrics for its components [43]. Components of an aeroplane such as, spoilers, rudders, doors, elevators, keel beams, fan blades, wings, rear bulkhead and other interior parts are made up of bio-fibre based composites [44, 45]. Apart from strength to weight ratio, flammability is also an important parameter to be considered while designing parts of aircrafts. Synthesizing bio-fibre composites possessing high flame resistance is one of the vital areas of research for aerospace industry [46]. Interior parts of an aircraft such as ceiling panels, cabinet walls, flooring etc. are made up of carbon reinforced thermoset composites. Though thermoset composites are good in flame resistance, they are poor in mechanical properties and also costlier

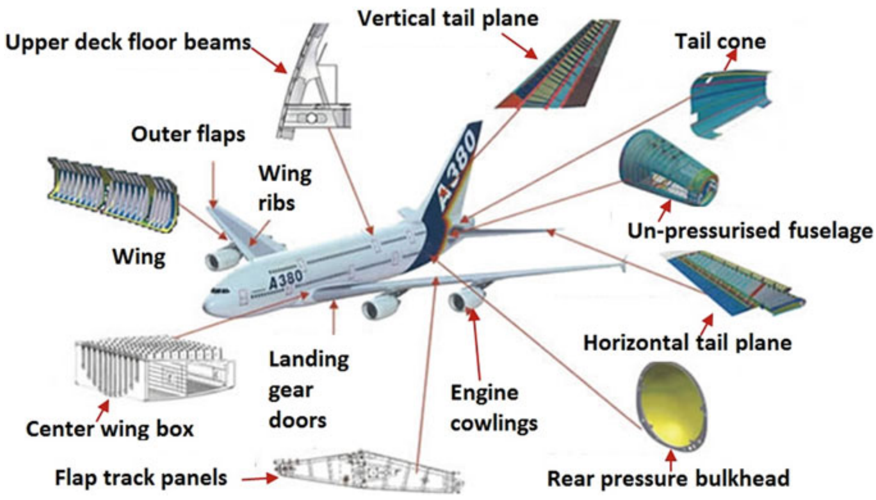


Fig. 3 Bio-fibre composites for various parts of an aircraft

as compared to that of other polymers. Hence, the researchers looked for an alternate hybrid composite made of bio-fibre which will balance flame resistance, mechanical characters and cost [47].

A research on the comparison between natural and artificial fibre composite has been made to study the suitability of materials for structural applications inside the aircraft by using sisal, basalt and glass as fibres in epoxy matrix. It has been divulged that, after comparing sisal-glass composite, sisal-basalt composite and sisal-glass-basalt composite, sisal-basalt composite produced optimum strengths and other characters as compared to that of the remaining ones and thus makes it apt for interior parts of aircraft. Aircraft wing boxes replaced by ramie fibre reinforced composites exhibited 14% reduction in weight as compared to that of the traditional materials [48]. Like this, diverse parts in an aircraft are made up of bio-fibre reinforced composite materials. Some of the parts are shown in Fig. 3.

4 Construction Industry

The Bio-fibre composites have wide applications for construction parts and they are proven to be useful under all weathering conditions. Coir fibre reinforced composites are deployed for producing house roofing and post boxes and the same is capable of retaining its characters for more than 6 years [49, 50]. Bio-fibres have been utilized as reinforcements in concrete matrix since the last decade. Though they are not on par with the characters of steel reinforcements, they are apt for light load applications where material cost can be saved to a notable extent. Coir reinforced panels have showed a high durability as they are not affected by sulphate and acid based environment. Jute fibre reinforced composites are tested for its characters and observed that, they are apt for underground pipes. During the development of composites, it has been recommended to keep the glass fibres as the skin layer and jute as inner layer for trenchless storage of liquid in the underground pipes [51].In another research, it has been proved that hemp and glass reinforced sandwich composites are more desirable for curved pipes and it reduces the manufacturing cost by 20% and weight by 23% [52].

Some bio-fibres when used along with a proper binder, behaves as a surrogate for wood in structural applications. Chopped sisal and woven jute in hybrid form along with fly ash and red mud is proven to replace wood and thus it reduces the cost of building construction [53, 54]. Studies on the flax fibre reinforced composite reported that, the fabricated composites are on par with the performance of conventional wood and hence they may be used for building roofs [55]. As there is a scarcity in wood, nowadays ply wood manufacturers are looking for alternate materials. Oil palm fibres serves as a good alternate for wood and thus by reinforcing the oil palm fibres in polymers, ply woods of high strength and durability could be produced in large quantity [56]. Many indagations have been made to envisage the strength and suitability of bio-fibre reinforced plastics for structural applications. Some of them are listed in Table 3.

Table 3 Applications of bio-composites in construction industry

S. No	Fibres/matrix	Application	References
1	Rice husk/ polyethylene	Window frames	[57, 58]
2	Bamboo/epoxy	Ceilings, partition board	[59]
3	Bagasse/ polyester	Medium density fibre board for partition walls	[60, 61]
4	Jute/Soybean oil based resin	I-sectioned beams	[62]
5	Sisal/cashew nut shell liquid	Roofing materials	[63, 64]
6	Coir, sisal and jute/cement mortar	Slabs for cupboards	[65]
7	Coir/cement mortar	Light weight cement board	[66]
8	Bamboo / bamboo	Park benches, bridge components and fences	[67]
9	Basalt/cement mortar	Horizontal beams	[68, 69]
10	Jute, glass/vinyl ester	Deck panels	[70]

5 Domestic Applications

Nowadays, bio-composites are replacing conventional plastic materials under several circumstances. Bio-fibre is suitable for floor mattress and cushions for chair, bed and sofas [71]. Banana fabric reinforced plastics are widely used for household appliances such as telephone stands and furniture and this reduces the cost of the product to a large extent as compared to that of the conventional wood and plastics [72, 73]. In the similar way, areca and maize powder reinforced plastics produced 40% more strengths as compared to the traditional particle board and it is suggested that maize and areca reinforced phenol composites are more preferable for domestic applications and packaging purposes [73, 75]. Bio-fibres find disparate usages for domestic purposes such as, carpet backing, wall decorations and yarns for woven mats that give ravishing look. Palm fibres along with natural resin is utilised in the form of flower pots and fruit trays. Starch and grass fibres are used for the preparation of table wares and plates and they have the capacity of degrading before 40 days [44]. Bamboo reinforced poly lactic acid composites are made in the form of packaging materials and it is suggested that they have the potential of replacing plastics. As bamboo has lofty impact properties, it is apt for both rigid and protective packaging [76]. Wood flour based composites are used for making perfume containers and bagasse is used for making mobile phone stands. Like this there are many domestic applications for bio-fibre composites. Some of them are depicted in Fig. 4.

6 Marine Industry

Bio-fibre composites have wide applications in marine industry. Majority of boats which are used for recreation, fishing and transport are made up of composite materials [77]. Water absorption is one of the important parameters which must be addressed while designing parts for marine application. As the materials are exposed to sea water for a long time, the material should have the resistance to absorb water and maintain the characters for a prolonged life. Generally, bio-fibres absorb water largely as compared to that of the synthetic fibres. Hence, in order to alleviate the water absorption, the bio-fibre must be covered by a thick layer of matrix resin along with a gel coat. This enhances the life of bio-fibres and the composite when used for marine applications. Based on this approach, a multi-hull has been prepared by using flax reinforced polyester composite with balsa and cork as the sandwich cores. The component has been tested after one year and it has been reported that, the material perpetuate all the mechanical characters without degradation [78]. Basalt and flax fibres have been used as skin layers during the design of a yacht desk hatch with poly vinyl chloride as the inner core. Basalt as the upper shell provides a hard dark surface whereas the flax at the bottom gives a brownish smooth internal surface. It has been realised that, basalt and flax are superior in all its characters as compared

Fig. 4 Bio-fibre composites for domestic applications

to that of the conventional carbon reinforcements. Furthermore, the bio-fibres also alleviate the cost of manufacturing to a notable extent [79].

A research on water absorption has been made by testing kenaf—polyester and alovera—polyester composites with inclusions of nanoclay. It has been realised that, the addition of nanoclay behaves like a barrier for water entry and thus elevated the resistance to water absorption of the composites [80, 81]. Another study has been conducted on water absorption by using luffa and coir as the reinforcements in epoxy matrix with silicon dioxide nanospheres as the fillers. It has been culminated that, the water absorption is significantly dwindled by the inclusion of silicon dioxide particles. The silicon dioxide reduces the free hydroxyl group of the bio-fibres and thus alleviates the hydrophilic character of composites. In addition, the silicon dioxide particle enhances the bonding strength between the bio-fibres and the surrounding matrix thereby elevating the mechanical characters of the composites to a remarkable extent [82, 83]. Almost similar result has been disclosed in another study on water absorption by using basalt reinforced epoxy with halloysite as the nanofillers. It has been unveiled that the decrease in water absorption is due to the one dimensional structure and high aspect ratio of the nanofillers that prevents the entry of water molecules by means of tortuous path [84].

7 Electrical and Electronic Applications

Natural fibres made from animal wastes are utilized by severalresearchers as reinforcements in composites. Each animal fibre is special in its character and hence they may be used for specific application. A research on chicken feather reinforced composite reported that, the chicken feather fibres augmented the mechanical strengths, flame retardation, thermal degradation and peel strength. This makes the composite desirable for development of printed circuit boards in electronic industries [85]. Low thermal expansion, low dielectric constant, loss factor, volume resistivity and low/high electrical conductivity are the vital characters required for electrical applications. Bio-fibre composites are deployed as terminals, connectors, switches, plugs, sockets, switch boards and circuit boards. The electrical properties of sisal fibre composites has been studied and disclosed that, it has electric anisotropic character [86, 87]. On the other hand, electronic industry uses the bi-fibre composites for fuel cell parts, electronic packaging, interconnections, thermistors, sensor components, interlayer dielectrics, lids, heat sinks and housings [88]. Hemp reinforced poly lactic acid composites are used for laptop casing and protective cap for lamp bulbs are made up of recycled paper pulp. On the other hand, coir fibre along with sepiolite rock particles as binder provides excellent thermal decomposition and helps in elevating the electrical conductivity of the composites. Hence coir based concrete composites are more suitable for electrical and sensor applications [89, 90].

Electromagnetic interference is an important phenomenon which affects both the performance of the electronic system as well as the biological system of human beings. Metal sheets are generally used for shielding for electromagnetic interference but they have poor mechanical and corrosion properties. In order to augment its properties, coating has been carried out by using copper, gold, silver and aluminium resulting in elevating the cost and time of manufacture [91, 92]. In order to overcome these difficulties, a probing has been made to study the electromagnetic behaviour of kenaf fibre reinforced polyester composite and showed that, the fabricated materials are ideal for electromagnetic shielding [93]. In another exploration, retted fibres are produced by soaking the carbon in $FeCl_3$ and $FeCl_2$ solutions for about 14 h. During this process, iron oxide particles are settled on the fibre surface and the fibres are said to be magnetized fibres. These magnetized fibres with 18% of iron particles produced a shielding efficiency of 80% at a frequency of 11 GHz. Though it is well proven that the composites have high shielding efficiency, it lacks in corrosion resistance. The corrosion resistance could be aggrandized by introducing bio-fibre layers at the extremities [94, 95].

8 Bio-medical Applications

The accomplishment of a bio-composite in medicinal field depends on disparate factors such as, surgical techniques adopted, health condition of the patient, immune system and life style of the patient. The compatibility of bio-composites in bio-medical applications is a vital factor before its usage [96]. The compatibility differentiates the capacity of fibre in terms of chemical, biological and physical suitability. Bio-composites are suitable for implant and they must have optimum stiffness during maximum loading at the implant/tissue interface [97].Bio-fibres in the form of powders sometimes exhibit unequalled characters such that they are capable of replacing conventional materials like stainless steel, titanium, cobalt, zirconium etc. One such research has been made by using bio-fibres such as roselle, banana and sisal in powdered form to make a plate for fractured bone. The research successfully proved that, the bio-fibre based composites are capable of serving as an alternate for conventional materials both for internal and external fixation [98, 99].

Many researchers have brought into play bio-fibres for bio-medical applications. Pineapple leaf fibre is found to be versatile for several bi-technological usages such as, drug delivery, medicinal implants, tissue engineering, etc. [100, 101]. Pineapple leaf fibre based nano composites are widely used in cardiovascular implants, articulate cartilage, urethral catheters, penile prostheses, and scaffolds for tissue engineering and as artificial skin [102]. On the other hand, nano fibres extracted from flax, hemp, rutabaga and kraft pulp celluloses are tested and approved for its suitability in blood bags, cardiac parts and as valves [103, 104]. Damaged and removed tooth are nowadays replaced by using bio-composite permanent implant. Apart from these, bio-fibre based composites also serves as a replacement for vascular grafts, pacemakers, biosensors etc. Composites made by using collagen silk are found to be ideal for lesioned tissues in human body. It has been observed that, an elevation in the silk content enhances the tensile strength and modulus of elasticity of the composites to a remarkable extent [105].

9 Musical Instruments

Properties of materials are not constant throughout the component structure. It varies according to its structure and other geometrical dimensions. This character is common in conventional materials whereas, it is highly reduced in bio-fibre composites. This makes bio-fibre composites more compatible for musical instruments. Apart from this, low production time and high resistance to environmental changes are also observed as vital characteristics for musical instruments [106]. Bamboo and wood fibres are widely used for developing musical instruments. Bio-fibre composites have been used as a fill-in for wood since 1975 in the top plates of violin, guitar and other string instruments [107]. A study on the characters of flax fibre composite divulged that, flax fibre composites showed promising behaviour as guitar board as compared to that of the conventional Sitka spruce [108]. Hemp and flax fibre reinforced in polypropylene matrix has been used for developing violin boards by Jacob Winter, a German based company. On the other hand, Blackbird, an American guitar manufacturer, uses linen fabric and bio-resin for developing guitar boards. It is observed that, the linen fabric guitars produced optimum acoustic characters as compared to that of the traditional wood based materials [109].

10 Other Industries

10.1 Energy Sector

Bio-fibre composites are playing a major role in all industries. During energy generation through solar panels, bio-fibre based hybrid composites are used as trough for energy collection from sun. The collectors used for collecting the solar energy is high due to its enhanced characters and this may be reduced to a notable extent by reinforcing bio-fibres and synthetic fillers in hybrid form without losing other properties [110, 111]. Weight reduction of wind turbine blades is a major concern for turbine manufacturers and this may be achieved by using bio-fibres as reinforcements. It has been recorded that, the performance of blades made of bio-fibre composites at low wind speeds are superior to the conventional materials and this may be achieved by using basalt fibres in place of carbon fibres [112].

10.1.1 Ballistic Applications

Kenaf fibre has been widely in several industries due to its durability and strength. A probing has been made to study the ballistic performance of composites comprising kenaf as an alternate for kevlar fibres. Kenaf reinforcements have been tested by placing it as the core layer, extreme layers and alternating layers. It has been identified that, kenaf when used as the skin layer produced consummate performance as compared to that of the other composites [113]. In addition it is also realized that, the hybridization of other fibres with kenaf exhibited as negative effect on the characters. In another study on the woven kenaf based composites reported that, woven kenaf along with kevlar in hybrid form produced superior performance on ballistics as compared to that of the nonwoven fibre based composites [114, 115].

10.2 Sporting Goods

Light weight, durability, low maintenance, thermal resistance, vibration resistance, high strength, design freedom etc., are the important parameters to be considered while manufacturing the sports goods. As majority of these are parameters are highly satisfied, bio-fibre composites are found to be apt for sporting goods [116]. At the inception, tennis racquets are made from wood based composite for its handle and natural gut of cow for its wires. The natural gut is observed to be promising for its strength and vibration properties. Several sporting tools such as, skis, wind surfing plates, badminton racquets, fishing rods, swords, golf club heads, cricket helmets, climbing ropes are manufactured by using bio-fibre composites [117].

11 Summary and Conclusion

Disparate investigations have been made since the last two decades to synthesize, fabricate and analyse the characters of bio-fibre reinforced composites. Many studies have also been done to assess the suitability of bio-fibre composites for specific application and it is revealed that bio-fibre composites are apt for all such applications. Although there are several characters for a composite material, each application needs some specific characters. Elevated strength to weight quotient, high biodegradability and cost reduction are the vital characters for a composite to be used for structural application. On the other hand, weight reduction and high resistance to water absorption are the primary characters required for marine applications. Light weight and high manoeuvrability are the required characters for sporting goods and bio-degradability and suitability are the vital properties for bio-medical applications. Like this, the composite material need to be synthesized, fabricated and tested before it is used for an application. Although, there have been many research works on diverse bio-fibres, the way towards it is not a cul-de-sac. Still there are several bio-fibres to be assessed for its characters and suitability. On the other hand, composites made of both bio-resin and bio-fibre is an important area where there is no adequate probing. Considering the bio-degradability as a major concern for technological research at all the times, the bio-composites are the far-reaching materials that rules and save the entire macrocosm.

References

1. Venkatakoteswararao G, Vinayagamoorthy R (2020) Review on thermal analysis of polymer matrix composites, IOP Conf. Series: Materials Science and Engineering, 954, 012037
2. Rajesh, G, Ratna Prasad AV, Gupta AVSSKS (2015) Mechanical and degradation properties of successive alkali treated completely biodegradable sisal fiber reinforced poly lactic acid composites. J Reinf Plast Compos 34:951–961
3. Vinayagamoorthy R, Kumar S, Kumar S, Sharan MS, Afzal GM, Rajamurugan TV (2021) Trends on the abrasive flow and electric discharge machining of polymer matrix composites. Advances in materials and manufacturing engineering, Lecture Notes in Mechanical Engineering, pp 43–53
4. Vinayagamoorthy R, Sivanarasimha S, Vinay Kumar KR, Padmanabhan V (2015) Characteristic investigations on loofah, jute and glass fiber reinforced sandwich polymeric composites. Appl Mech Mater 813–814:14–18
5. Zwawi M (2021) A Review on Natural Fiber Bio-Composites, Surface Modifications and Applications. Molecules 26:1–28
6. A. Ticoalu, T. Aravinthan, F. Cardona (2010), A review of current development in natural fiber composites for structural and infrastructure applications, Proceedings of the Southern Region Engineering, Conference (SREC '10), 113–117, Toowoomba, Australia, November 2010.
7. R. Vinayagamoorthy, K. S. Subrahmanyam, K. Murali Krishna Murthy, K. Arun Prajwar, P. Gopinath, M. Sai Lahari, K. PruthviRangan (2020), Influence of nanoparticles on the characters of polymeric composites, IOP Conf. Series: Materials Science and Engineering, 954, 012026.
8. Vishnu Vardhini KJ, Murugan R, Surjit R (2017) Effect of alkali and enzymatic treatments of banana fibre on properties of banana/polypropylene composites. J Ind Text 47:1849–1864
9. M. J. Mochane, T. C. Mokhena, T. H. Mokhothu, A. Mtibe, E. R. Sadiku, S. S. Ray, I. D. Ibrahim, O. O. Daramola (2019), Recent progress on natural fiber hybrid composites for advanced applications: A review, eXPRESS Polymer Letters, 13, 159–198.
10. Layth Mohammed MNM, Ansari GP, Mohammad Jawaid M, Islam S (2015) A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. International Journal of Polymer Science 2015:1–15
11. Rajmohan T, Vinayagamoorthy R, Mohan K (2019) Review on effect machining parameters on performance of natural fibre–reinforced composites (NFRCs). J Thermoplast Compos Mater 32:1282–1302
12. T. Shito, K. Okubo, T. Fujii (2002), Development of eco-composites using natural bamboo fibers and their mechanical properties, High Performance Structures and Composites, 1–8.
13. Faruk O, Bledzki AK, Fink HP, Sain M (2012) Biocompositesreinforced with natural fibers: 2000–2010. Progress in PolymerScience 37:1552–1596
14. Vinayagamoorthy R (2020) Influence of fibre pretreatments on characteristics of green fabric materials. Polym Polym Compos. https://doi.org/10.1177/0967391120943461
15. Bharath KN, SatyappaBasavarajappa, (2016) Applications of biocomposite materials based on natural fibers from renewable resources: a review. Sci Eng Compos Mater 23:123–133
16. G. Venkatakoteswara Rao, R. Vinayagamoorthy, K. Abinesh, M. Sudharsan, S. Ponmeganathan, L. S. Deepak Kumar (2021), Influence of Chemical Treatment on Natural Fibers: A Review, Advances in Materials and Manufacturing Engineering, Lecture Notes in Mechanical Engineering, 533–538.
17. Thiruchitrambalam M, Alavudeen A, Venkateshwaran N (2012) Review on kenaf fiber composites. Review on Advanced MaterialScience 32:106–112
18. Fu Z, Suo B, Yun R, Lu Y, Wang H, Qi S, Jiang S, Lu Y, Matejka V (2012) Development of eco-friendly brake friction composites containing flax fibers. J Reinf Plast Compos 31:681–689

19. Vinayagamoorthy R (2019) Effect of particle sizes on the mechanical behaviour of limestone-reinforced hybrid plastics. Polym Polym Compos. https://doi.org/10.1177/0967391119883163
20. Thilagavathi G, Pradeep E, Kannaian T, Sasikala L (2010) Development of Natural Fiber Nonwovens for Application as Car Interiors for Noise ControlJournal of. Industrial Textiles 39:267–278
21. Boopathi L, Sampath PS, Mylsamy K (2017) Design and Fabrication of Two Wheeler Mudguard using Sisal Natural Fiber. SSRG International Journal of Mechanical Engineering 1:1–5
22. Vinayagamoorthy R, Koteshwar TN, Madhav VajhalaVenu, Sai TK, Konda V (2019) Drilling associated parametric investigations on chemically treated natural fiber composite. Materials Today: Proceedings 16:277–283
23. Ahmed KS, Vijayarangan S, Rajput C (2006) Mechanical Behavior of Isothalic Polyester-based Untreated Woven Jute and Glass Fabric Hybrid Composites. J Reinf Plast Compos 25:1549–1569
24. Jawaid M, Abdul Khalil HPS (2011) Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. CarbohydratePolymers 86:1–18
25. Vinayagamoorthy R (2020) Trends and Challenges on the Development of Hybridized Natural Fiber Composites. Journal of Natural Fibers 17:1757–1774
26. Shinoj S, Visvanathan R, Panigrahi S, Kochubabu M (2011) Oil palm fiber (OPF) and its composites: a review. Ind Crops Prod 33:7–22
27. B. C. Suddell (2008), Industrial fibres: recent and current developments, Proceedings of the Symposium on Natural Fibres, 20, 71–82, FAO, CFC, Rome, Italy, October.
28. R. Vinayagamoorthy, I. V. Manoj, G. Narendra Kumar, I. Sai Chand, G. V. Sai Charan Kumar, K. Suneel Kumar (2018), Challenges on the synthesis, characterization and machining of green fiber plastics: A review, IOP Conference Series: Materials Science and Engineering, 390, 012029.
29. Pickering K (2008) Properties and Performance of Natural-Fibre Composites. Woodhead Publishing, Cambridge, UK
30. Ku H, Wang H, Pattarachaiyakoop N, Trada M (2011) A review on the tensile properties of natural fiber reinforced polymer composites. Compos B Eng 42:856–873
31. Vinayagamoorthy R (2019) Influence of fiber surface modifications on the mechanical behavior of Vetiveriazizanioides reinforced polymer composites. Journal of Natural Fibers 16:163–174
32. Chandramohan D, Bharanichandar J (2013) Natural Fiber Reinforced Polymer Composites for Automobile Accessories. American Journal of Environmental Science 9:494–504
33. Brouwer WD (2000) Natural fibre composites: Where can flax compete with glass. SAMPE J 36:18–23
34. Vinayagamoorthy R, Rajeswari N, Vijayshankar S, Vivekanandan M, Sri ramamurthybellala, K.R. Venkata subramaniam, (2014) Surface and sub-surface analysis of hybrid polymer composites during machining operations. Procedia Material Science 5:2075–2083
35. Peças P, Carvalho H, Salman H, Leite M (2018) Natural Fibre Composites and Their Applications: A Review. Journal of Composite Science 2:1–20
36. Väisänen T, Das O, Tomppo L (2017) A review on new bio-based constituents for natural fiber-polymer composites. J Clean Prod 149:582–596
37. Vinayagamoorthy R, Rajeswari N (2014) Mechanical performance studies on Vetiveriazizanioides/jute/glass fiber-reinforced hybrid polymeric composites. J Reinf Plast Compos 33:81–92
38. Witayakran S, Smitthipong W, Wangpradid R, Chollakup R, Clouston PL (2017) Natural Fiber Composites: Review of Recent Automotive Trends, Reference Module in Materials Science and Materials Engineering;Elsevier Publishing: Amherst. MA, USA
39. Gurunathan T, SanjayNayak SK (2015) A review of the recent developments in biocomposites based on natural fibres and their application perspectives. Compos A Appl Sci Manuf 77:1–25

40. MiLi,YunqiaoPu, M. ValerieThomas, Chang GeunYoo, SoydanOzcan, YulinDeng, KimNelson, Arthur J.Ragauska (2020), Recent advancements of plant-based natural fiber–reinforced composites and their applications, Composites Part B: Engineering, 200, 108254.
41. Ashworth S, Rongong J, Wilson P, Meredith J (2016) Mechanical and damping properties of resin transfer moulded jute-carbon hybrid composites. Composites Part B-Engineering 105:60–66
42. Flynn J, Amiri A, C. lven, (2016) Hybridized carbon and flax fiber composites for tailored performance. Mater Des 102:21–29
43. Vinayagamoorthy R, SaswathKaundinya SL, Mani Teja GLSN, Adithya K (2016) A Study on the Properties of Natural Sandwich Laminates. Indian J Sci Technol 9:1–6
44. Gupta G, Kumar A, Tyagi R (2016) Application and Future of Composite Materials: A Review. International Journal of Innovative Research in Science, Engineering and Technology 5:6907–6911
45. J. Hinrichsen (2000), The Material Down-selection Process for A3XX, CAES, 19th European Conference on Materials for Aerospace Applications, Munich, 6–8.
46. Szolnoki B, Bocz K, Soti PL, Bodzay B, Zimonyi E, Toldy A, Morlin B, Bujnowicz K, Władyka-Przybylak M, Marosi G (2015) Development of natural fibre reinforced flame retarded epoxy resin composites. Polym Degrad Stab 119:68–76
47. Vinayagamoorthy R, Sivanarasimha S, Padmanabhan V, Vedula Ganesh S, Karthikeyan, (2015) Experimenal studies on Water absorption and Thermal degradation of Natural Composites. Int J Appl Eng Res 10:663–668
48. Alexander J, Churchill SJE (2017) Mechanical characterization of baslat based natural hybrid composites for aerospace applications. IOP Conference Series: Materials Science and Engineering 197(012008):1–8
49. Roy SB, Shit SC, Sengupta RA, Shukla PR (2014) A Review on Bio-Composites: Fabrication, Properties and Applications, International Journal of Innovative Research in Science. Eng Technol 3:16814–16824
50. Vinayagamoorthy R, Rajmohan T (2018) Machining and its challenges on bio-fibre reinforced plastics: A critical review. J Reinf Plast Compos 37:1037–1050
51. R. Vinayagamoorthy (2020), Mechanical performance of glass- and biofibre-reinforced hybrid composites, Glass Fibre-Reinforced Polymer Composites, 1–16.
52. Yu HN, Kim SS, Hwang IU, Lee DG (2008) Application of natural fiber reinforced composites to trenchless rehabilitation of underground pipes. Compos Struct 86:285–290
53. Cicala G, Cristaldi G, Recca G, Ziegmannb G, El-Sabbaghb A, Dickert M (2009) Properties and performances of various hybrid glass/natural fibre composites for curved pipes. Mater Des 30:2538–2542
54. Saxena M, Morchhale RK, Asokan P, Prasad BK (2008) Plant Fiber- Industrial Waste Reinforced Polymer Composites as a Potential Wood Substitute Material. J Compos Mater 42:367–384
55. Vinayagamoorthy R, Konda V, Tonge P, Koteshwar TN, Premkumar M (2019) Surface roughness analysis and optimization during drilling on chemically treated natural fibercomposite. Materials Today: Proceedings 16:567–573
56. Dweib MA, Hu B, Donnell AO, Shenton HW, Wool RP (2004) All natural composite sandwich beams for structural applications. CompositeStructures 63:147–157
57. Abdul Khalil HPS, Nurul Fazita MR, Bhat AH, Jawaid M, Nik Fuad NA (2010) Development and material properties of new hybrid plywood from oil palm biomass. Mater Des 31:417–424
58. Vinayagamoorthy R (2020) Friction and wearcharacteristics of fibrereinforcedplasticcomposites. Journal of Thermoplastic CompositeMaterials 33:828–850
59. Rahman WAWA, Sin LT, Rahmat AR (2008) Injection Molding Simulation Analysis of Natural Fiber Composite Window Frame. J Mater Process Technol 197:22–30
60. Mishra SC (2009) Low Cost Polymer Composites with Rural Resources. J Reinf Plast Compos 28:2183–2188
61. R. Vinayagamoorthy, Ankur Sharma, Vignesh Iyer, G. Navneeth (2019), Investigation of Surface Damagesin Hole Making on Luffa/Jute/GlassReinforced Plastics, Advances in Manufacturing Processes, Lecture Notesin Mechanical Engineering, 521–532.

62. Alms B, Yonko PJ, McDowell RC, Advani SG (2009) Design anddevelopment of an I-Beam from natural composites. Journal ofBiobased materials and Bioenergy 3:181–187
63. Bisanda ETN (1993) The Manufacture of Roofing Panels from Sisal FiberReinforced Composites. J Mater Process Technol 38:369–379
64. Vinayagamoorthy R, Manoj IV, Narendra Kumar G, Sai Chand I, G. V. Sai Charan Kumar, K. Suneel Kumar, (2018) A central composite design based fuzzy logic for optimization of drillingparameters on natural fiber reinforced composite. J Mech Sci Technol 32:2011–2020
65. Ramakrishna G, Sundararajan T (2005) Studies on the durability of natural fibres and the effect of corroded fibres on the strength of mortar. Cement Concrete Composites 27:575–582
66. Asasutjarita C, Hirunlabha J, Khedarid J, Charoenvaia S, Zeghmatib B, Cheul Shin U (2007) Development of coconut coir-based lightweight cement board. Constr Build Mater 21:277–288
67. Bakis CE, Bank LC, Brown VL (2012) Fiber-ReinforcedPolymer Composites for Construction-State-of-the-Art Review. J Compos Constr 6:73–87
68. Vinayagamoorthy R, Rajeswari N (2012) Analysis of cutting forces during milling of natural fibered composites using fuzzy logic. International Journal of Composite Materials and Manufacturing 2:15–21
69. Abed F, Alhafiz AR (2019) Effect of basalt fibers on the flexural behavior of concrete beams reinforced with BFRPbars. Compos Struct 215:23–34
70. Gopinath R, Poopathi R, Saravanakumar SS (2019) Characterization and structural performance of hybridfiber-reinforced composite deck panels. Advanced Composites and Hybrid Materials 2:115–124
71. Vinayagamoorthy R (2017) A review on the polymeric laminatesreinforced with natural fibers. J Reinf Plast Compos 36:1577–1589
72. Ashori A, Nourbakhsh A, Karegarfard A (2009) Properties of Medium Density Fiberboard Based on Bagasse Fibers. Journal of CompositeMaterials 43:1927–1934
73. Sapuan SM, Maleque MA (2005) Design and fabrication of natural woven fabric reinforced epoxy composite for household telephone stand. Mater Des 26:65–71
74. Vinayagamoorthy R, Venkatakoteswararao G (2020) Synthesis and property analysis of green resin-based composites. J Thermoplast Compos Mater 33:1429–1445
75. Bharath KN, Swamy RP, Mohan Kumar GC (2010) Experimental studies on biodegradable and swelling characteristics of natural fibers composites. International Journal of Agricultural Science 2:1–4
76. Nurul Fazita MR, Jayaraman K, Bhattacharyya DA (2013) Performance study on composites made from bamboo fabric and poly (lactic acid). The International Journal of Advanced Manufacturing Technology 32:1513–1525
77. Vinayagamoorthy R, Madhavan S (2011) Performance studies on shrink-fit radial fan assembly using finite element analysis. International Journal of Business Review and Manufacturing Management 1:5–8
78. Peter D (2016) Environmental degradation of composites for marine structures: new materials and new applications. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 374:1–13
79. Cristiano Fragassa, Marine Applications of Natural Fibre-Reinforced Composites: A Manufacturing Case Study, Advances in Applications of Industrial Biomaterials, 21–47.
80. P. Ramesh, B.D. Prasad, K. Narayana (2020), Influence of Montmorillonite Clay Content on Thermal, Mechanical, Water Absorption and Biodegradability Properties of Treated Kenaf Fiber/PLA-Hybrid Biocomposites, Silicon, 1–10.
81. P. Ramesh, B.D. Prasad, K. Narayana (2019), Effect of MMT Clay on Mechanical, Thermal and Barrier Properties of Treated AloeveraFiber/PLA-Hybrid Biocomposites,Silicon, 1–10.
82. Vinayagamoorthy R, Mothilal T, Madhavan S (2009) Performance enhancement of a diesel engine by providing insulations on engine parts. International Journal on Design and Manufacturing Technologies 3:63–67
83. K. Anbukarasi, S.I. Hussain, A.A. Roseline, S. Kalaiselvam (2019), Effect of SiO2 nanospheres on mechanical, thermal and water absorption behaviours of lu_a-coir/epoxy hybrid composites, Materials Research Express, 6, 125618.

84. Miao YG, Liu HY, Suo T, Mai YW, Xie FQ, Li YL (2016) Effects of strain rate on mechanical properties of nanosilica/epoxy. Compos B Eng 96:119–124
85. Zhan M (2013) Design and evaluation of bio-based composites for printed circuit board application. Compos A 47:22–30
86. Kannan P, Balasubramanian K, Vinayagamoorthy R (2015) Defect Reduction in Ring Blank Casting Through Design of Experiments. International Review of Mechanical Engineering 9:536–541
87. Kumar S, Sangwan P, Dhankhar R, V. Mor V, (2013) Utilization of Rice Husk and Their Ash: A Review. Research Journal of Chemical and Environmental Sciences 1:126–129
88. Yakovenko O, Matzui L, Danylova G (2017) Electrical Properties of Composite Materials with Electric Field-Assisted Alignment of Nanocarbon Fillers. Nanoscale Res Lett 12:471
89. Satyanarayana KG, Sukumaran K, Mukherjee PS, Pavithran C, Pillai SGK (1990) Natural fibre-polymer comosites. Cement Concr Compos 12:117–136
90. Bispo TS, Barin GB, Gimenez IF, Barreto LS (2011) Semiconductor carbon composite from coir dust and sepiolite. Mater Charact 62:143–147
91. Vinayagamoorthy R, Rajeswari N, Karthikeyan S (2015) Investigations of damages during drilling of natural sandwich composites. Appl Mech Mater 766–767:812–817
92. Ding Z, Shi SQ, Zhang H, Cai L (2001) Electromagnetic shielding properties of iron oxide impregnated kenaf bast fiberboard. Compos B Eng 78:266–271
93. Xia C, Ren H, Shi SQ, Zhang H, Cheng J, Cai L, Chen K, Tan HS (2016) Natural fiber composites with EMI shielding function fabricated using VARTM and Cu film magnetron sputtering. Appl Surf Sci 362:335–340
94. Xia C, Yu J, Shi SQ, Qiu Y, Cai L, Wu HF, Ren H, Nie X, Zhang H (2017) Natural fiber and aluminium sheet hybrid composites for high electromagnetic interference shielding performance. Compos B Eng 114:121–127
95. Vinayagamoorthy R, Rajeswari N, Karuppiah B (2014) Optimization Studies on Thrust Force and Torque during Drilling of Natural Fiber Reinforced Sandwich Composites. Jordan J Mech Indust Eng 8:385–392
96. Xia C, K. Wang K, Y. Dong, S. Zhang, S.Q. Shi, L. Cai, H. Ren, H. Zhang, J. Li, (2016) Dual-functional natural-fiber reinforced composites by incorporating magnetite. Compos B Eng 93:221–228
97. Ramakrishna S, Mayer J, Wintermantel E, Leong KW (2001) Biomedical applications of polymer-composite materials: A review. Composite Science and Technology 61:1189–1224
98. Vinayagamoorthy R (2018) A review on the machining of fiber-reinforced polymeric laminates. J Reinf Plast Compos 37:49–59
99. Chandramohan D, Marimuthu K (2011) Analysis on natural fiber bone plates, European. J Exp Biol 54:384–406
100. Cherian B, Leao A, Souza D, Thomas S, Pothan L (2010) Isolation of nanocellulose from pineapple leaf fibres by steam explosion. Carbohyd Polym 81:720–725
101. Vinayagamoorthy R (2017) Parametric optimization studies on drilling of sandwich composites using the Box-Behnken design. Materials and Manufacturing Processess 32:645–653
102. Giri J, Adhikari R, Campus T (2013) A brief review on extraction of nanocellulose and its applications. Nepal Journals Online 9:81–87
103. Bhanagar A (2005) Properties of Cellulose nanofiber-reinforced composites. J Reinf Plast Compos 24:1259–1268
104. Ambiga K, Annadurai R, Vinayagamoorthy R (2016) Nitrate and Chromium Contamination in Groundwater from Effluent of Tanneries and Drastic Vulnerability Index Map – A Case Study of Ranipet area. Vellore District, Tamilnadu, Indian Journal of Science and Technology 9:1–13
105. Zhu B, Li W, Lewis RV, Segre CU, Wang R (2014) E-Spun composite fibers of collagen and dragline silk protein: Fiber mechanics, biocompatibility, and application in stem cell differentiation. Biomacromol 16:202–213
106. Yakovenko O, Matzui L, Danylova G (1998) Composite materials for musical instruments: The maturity. The Journal of the Acoustical Society of America 103:1105–1106

107. Phillips S, Lessard L (2011) Application of natural fiber composites to musical instrument top plates. J Compos Mater 46:145–154
108. Vinayagamoorthy R, Karthikeyan S, Prem Bhargav RS, Rajivalochan TV (2015) Properties investigations on metallic fiber reinforced sandwich composites. Appl Mech Mater 813–814:101–105
109. Kamrun N, Keya AN, Kona AF, Naimul KM, Islam AR, Khan, (2019) Natural fiber reinforced polymer composites: history, types, advantages and applications. Materials Engineering and Research 1:69–85
110. K.S. Reddy, H. Singla (2017), Optimization of woven jute/glass fibre-reinforced polyester hybrid composite solar parabolic trough collector. IOP Conference Series: Materials Science and Engineering, 222, 012016.
111. Vinayagamoorthy R, Rajeswari N, Sivanarasimha S, Balasubramanian K (2015) Fuzzy based optimization of thrust force and torque during drilling of natural hybrid composites. Appl Mech Mater 787:265–269
112. Chikhradze NM, Marquis FDS, Abashidze GS (2015) Hybrid fiber and nanopowder reinforced composites for wind turbine blades. J Market Res 4:60–67
113. Yahaya R, Sapuan SM, Jawaid M, Leman Z, Zainudin ES (2014) Quasi-static penetration and ballistic properties of kenaf–aramid hybrid composites. Mater Des 63:775–782
114. Vinayagamoorthy R, Rajeswari N, Vijayshankar S, Balasubramanian K (2014) Drilling Performance Investigations on Hybrid Composites by Using D-Optimal Design. International Review of Mechanical Engineering 8:952–961
115. Yahaya R, Sapuan SM, Jawaid M, Leman Z, Zainudin ES (2016) Measurement of ballistic impact properties of woven kenaf–aramid hybrid composites. Measurement 77:335–343
116. Wang JL (2002) Application of Composite Materials on Sports Equipments. Appl Mech Mater 155:903–906
117. Vinayagamoorthy R, Subramanyam KG, Kumar TN, Reddy YerasiHarshavardhan (2016) Modeling and Analysis of Drilling Induced Damages on Hybrid Composites. Indian J Sci Technol 9:1–10

Different Natural Fiber Reinforced Composites and Its Potential Industrial and Domestic Applications: A Review

Satish Babu Boppana, K. Palani Kumar, A. Ponshanmugakumar, and Samuel Dayanand

Abstract In recent years, considerable attention has been paid to the development and use of natural fibres since they are eco-friendly, renewable and reasonably economical. Natural fibres can be suitably used as a substitute for synthetic materials since they are lesser in weight and can conserve energy. They are available in abundance and incur low costs during harvesting. They happen to be budding materials, and when reinforced with a suitable matrix, they can substitute metal-based materials/composites that are presently used in aerospace and automotive industries. On the other hand, synthetic fibers are known to generate toxic byproducts and pose issues in recycling. However, natural fibers are prone to degradation when they are exposed to the external environment. The fibers pose a challenge while mixing with the polymer matrix. Surface modification of fibers is effectively carried out to overcome the weak interfacing bonding between the polymer and fibers. With the ever-growing environmental concern and excessive usage of petroleum-based reserves, the world is looking to develop composites that are compatible with the environment. In order to have a healthier impact on the environment, industries are often craving to use eco-friendly materials. The present paper focuses on the research work carried out by various investigators for synthesizing bio fiber-based composites aimed at using them in a variety of engineering fields.

Keywords Bio-fibers · Natural fibers · Applications · Natural fiber Composites · Renewable · Biodegradable · Polymers

S. B. Boppana (✉)
Department of Mechanical Engineering, School of Engineering, Presidency University, Bangalore, India

K. Palani Kumar · A. Ponshanmugakumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, Chennai 600044, India

S. Dayanand
Department of Mechanical Engineering, Government Engineering College, Gangavathi 583227, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_4

1 Introduction

Over the past few years, owing to the rigorous consumer's consciousness focusing on new products being manufactured, there has been a dramatic shift towards recycling and green manufacturing.

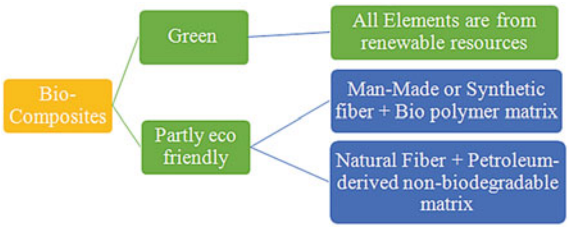
The composite material first used in early days of human history was related to clay reinforced with straw. The material was developed roughly around 3000 years ago. The composite would be termed as natural fiber composite, but with the development of technologies related to manufacturing while concentrating on better strength, metals, ceramics and synthetic fibers were found to gradually replace the traditional material using clay and straw.

Nowadays, the practice of using composites synthesized through natural fibers has become very popular in almost all fields concerned with engineering. This may be because the materials processed using bio fibers exhibit nearly the same characteristics as conventional materials. Few features that excel for the bio fibre-based composites would be properties related to lightweight, lesser cost of materials, and more importantly, their environmentally friendly aspect. Day by day, consumers are more inclined to think over products manufactured through an environmentally friendly process. It was during this change in approach that led to the development of composite materials. Traditional methods were supposed to be adopted during the synthesis of new composite materials more sustainably. In Fig. 1, classification of bio-composites are explained.

There is a need for sustainable usage of bio-composites to overcome the ecological imbalance due to the petroleum-related synthetic-based resources. Artificial fibers related to polymer-based composites have to be substituted by fibers available in biodegradable and natural form. The various types of natural fibre reinforcement methods are listed in Fig. 2.

Table 1 explains the international standards based on bio-based, biodegradable and compostable standards. A thorough study about the applications of composites reinforced with various natural fibers in various engineering fields is carried out since bio fibers are available abundantly and can be renewed; they also happen to be non-toxic and relatively cheap. Table 2 gives the broad classification of natural fibers.

Fig. 1 Classification of bio-composites



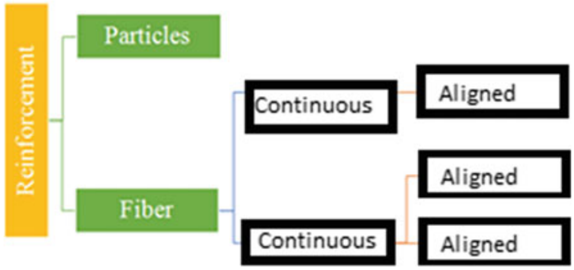


Fig. 2 Types of natural fibre reinforcement

Table 1 Bio-based, biodegradable, and compostable standards from the International Organization for Standardization (ISO)

Label	ISO Standard	Description
Bio-based	16620:2015	Describes the general ideas and calculation procedures for using the radiocarbon method to determine the amount of bio-based material in plastic products
Biodegradable	14852: 2018	Specifies a method for determining the degree of aerobic biodegradability of plastic materials by measuring the amount of carbon dioxide released
Compostable	17088:2012	Specifies the methods and requirements for identifying and labelling plastics and plastic-based products

Table 2 Natural fibre classification

Natural fibre	Cellulose/Lignocellulose	Bast Seed Fruit Stalk Grass / Reed Leaf Wood	Hemp, Flax, Jute, Ramie, Kenaf Cotton, Kapok Coir Wheat, Maize, Oat, Rice Bamboo, Corn Abaca, Banana, Pineapple, Sisal Hardwood, Softwood (e.g., Eucalyptus)
	Animal	Wool / Hair	Cashmere, Horsehair
	Mineral	-	Asbestos, Ceramic fibres

2 Natural Fibre Reinforced Composites Have a Variety of Applications

2.1 Coir Fiber-Strengthened Composite

The coir-based composites are extensively used in the aerospace industry and automotive industry. The wings, tails and propellors in the aircraft are the specific areas substituted by these composites. Particleboards [1], materials related to packaging [2] and mortar prepared by cement sand [3] have been associated with the use of

Fig. 3 Application of coir fibre in automobile

coir-based composites. Decks, panels, and slabs related to lightweight component members in structural fields also indicate the use of the above-mentioned composites. Figure 3 represents the thermal insulation provided by using coir related composites in areas like cushioning of seats in automotive sectors [4, 5]. Researchers have also been successful in designing water and other liquid storage tanks [6]. Considering the research carried out in finding hardness, flame retardancy and tensile properties of polypropylene composites reinforced with coir fiber, an optimal panel design was prepared for applications in interiors of automotive applications [7] through a suitable weight proportion mixture of coir fiber, polypropylene powder and maleic anhydride grafted polypropylene.

2.2 Kenaf Fibre-Fortified Composite

Polylactic acid thermoplastic, polypropylene and epoxy resin-based matrix materials fortified with kenaf fiber are used in bearings, tooling and some automotive parts. Pultrusion and compression moulding methods are often used to synthesize these kinds of composites. The kenaf fibers have tensile strength and Young's modulus in the range of 223–1191 MPa and 11-60GPa [8]. Hybrid kenaf/glass fiber-reinforced polymer composites showed enhanced mechanical properties with rain erosion resistance and found suitable for aircraft application [9].

Presently, kenaf is used in the production of paper. Kenaf is found to have superior properties in terms of toughness and improved aspect ratio compared to other fibers. Kenaf fibers are also used in product applications such as summer forage, potting media and animal bedding [10].

Owing to its lightweight, kenaf-based composites have reduced emissions and fuel consumption when used in automotive sectors. The composites are also used in Lexus package shelves. Figure 4 reveals the kenaf fiber based applications in automotive sectors. The exterior and interior parts of automotive structural members can be effectively manufactured. The beams of the bumper and parts related to front end modules in automotive vehicles can be effectively used with the help of twisted kenaf hybrid material [11].

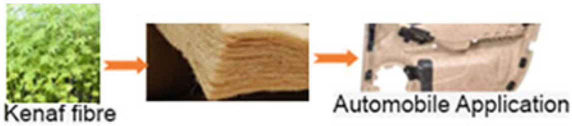


Fig. 4 Application of kenaf fibre in automobile

Fig. 5 Ramie fibre application in packaging and Insulation

2.3 Ramie Fibre-Strengthened Composites

Ramie fibers are used as sewing thread, handkerchiefs, weaving canvas, fabrics related to parachutes. The body armour and some applications in the civil field are also linked to the usage of ramie fiber since it has nearly the same specific stiffness as that of glass fiber. It has also used in the making of blouses, skirts, shirts and papers, and banknotes.

The specific applications involve ramie-based fabric centric epoxy composite bulletproof material. The conventional material used is heavier than the epoxy composite since it comprises steel and ceramics. Socket prosthesis was also achieved by using the fiber as mentioned earlier in epoxy matrix. Aluminium sheets were inserted with ramie fiber in the epoxy matrix to synthesize laminated composites in another application. Compared to aluminium, the tensile strength of the composite is relatively improved than that of aluminium. Ramie whiskers in nano form can also be used to prepare polymer-based electrolytes using polyoxyethylene [12]. Further, short ramie fiber reinforced soy protein-based polymer composites can be used in packaging and skins of appliances, whereas the long fibre-based composites can be effectively used in transportation and structural uses [13]. Figure 5 represents some applications in packaging related areas.

2.4 Flax Fibre-Fortified Composite

Researchers have worked on the possibility of using epoxy reinforced flax composite in the form of tube as concrete confinement. The compressive strength of the composite in the axial direction was superior when compared with the unconfined concrete. The other benefit would owe to its light weight-related framework. Tube made with flax reinforced composite covered the concrete as bridge pier [14]. Flax based composites with vegetable oil-based epoxy resin could be used in construction and automotive sectors (Fig. 6).

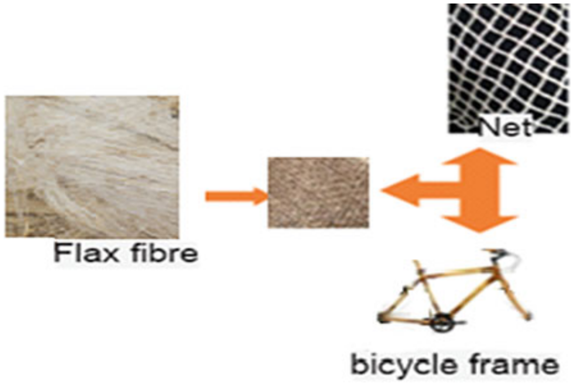


Fig. 6 Flax fibre application

Naturally available phenolic resin-like tannin strengthened with flax offers considerable benefits by lowering the ecological footprint of lighter weight applications in the automotive field corresponding to panels and trims of body and crash elements [15]. Gopalan et al. [16] suggest that flax woven epoxy-based composite can also be used in applications related to interiors of car, rail, panels of aircraft and equipment related to sports. Composites with flax fibers are used in frames of windows, decking, fencing, frame of bicycle, fork and snowboarding. Polypropylene based flax fiber composites are used in floor trays of cars. The interior door lining panels of few luxury cars also involve the use of flax fibre-based composites [17].

2.5 Jute Fibre-Strengthened Composite

Composite boards prepared from jute-coir are often superior when compared to plywood boards and can be used as backing for sleeper berths in railway coaches and fishing boats. Even the interiors of building, windows and doors have potential applications using board processed using jute. Gon et al. [18] emphasised the idea of using jute-based composites in backrest and backings of seats of vehicles. El-Sayed et al. [19] fabricated jute-based polymer composites for bearing applications.

Toilet blocks were successfully developed with the help of jute fiber reinforced plastic (FRP). Door shutters were sandwiched by FRP and synthesized within a short period that find importance during the aftermath of disaster relief. Other potential applications of jute-based composites were related to making doors using jute and FRP. The principal materials to support them could be foam using polyurethane and polystyrene. They can be used in construction fields like schools, offices and labs. Resin-jute based materials were also used to develop packaging resources for commodities like tea and fruits [18]. Gopinath et al. [20] highlighted the use of polyester-based jute composites in paperweights, false ceilings, shower, partition panels, tiles on roof, lampshades and bath units. Jute and phenolic based composite found a potential application to replace steel material used in slipway primarily used

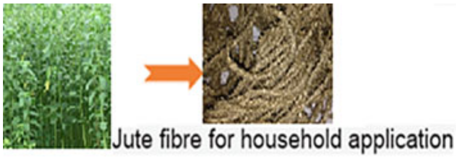


Fig. 7 Jute fibre applications

for launching lifeboats since they were found to reduce the coefficient of friction. Figure 7 represents application of jute fiber in making ropes.

2.6 Sisal Fiber-Strengthened Composite

Sisal fibers possess good strength of around 640 MPa, hence they are used in making ropes, carpets and mats. The fibers have low density with good modulus and hence can be potential candidates for applications in wall hangings and purses.

Swift [21] developed sisal/cement composites for structural applications. They were suitable for cladding walls that consisted of adobe structures which were resistant to earthquake. Water ducts, bins for storing grains were few other applications of the composites. Medhi et al. [22] reported the mechanical behaviour of sisal reinforced polymer composite and highlighted the potential to be used in industrial and automotive sectors. The other possible applications of the composite include laminates and construction-related material.

Researchers [23] have worked on cement-based long sisal fiber composite for their use in panels as structural members and were found to be resistant against impact and blast. The masonry walls which were not reinforced could be strengthened by using the composite. Sisal fiber reinforced resin-based composite was used to prepare brake pads that could possibly substitute pads using asbestos [24]. Glove box and door panels of cars were prepared by using sisal reinforced polymer composites, while the sisal/flax fibre-reinforced polyurethane-based composite was used in panels of door trim. The interior door lining of few cars was also substituted by sisal and flax-based composites [17]. Figure 8 represents the use of fiber in construction field.

Fig. 8 Sisal fibre applications

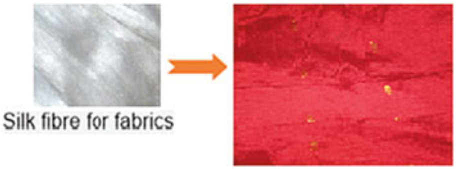


Fig. 9 Silk fibre applications

2.7 *Silk Fiber-Fortified Composite*

Silk fibers are of prime importance as natural fibers since it is found to be biocompatible and possess high toughness. They are used in clinical fields in the form of braided suture threads in surgical operations. The support structure for cartilage in medical fields also composes of silk fiber. The other fields related to the use of silk fibers is in the textile industry. Since silk fiber is relatively costlier than most other natural fibers, the waste obtained from the silk manufacturing industry is used as a supporting material for polymer-based composites. The polymer composites have the potential to be used in structural applications. The fibers are suitable as an alternative for glass fibers used as fortifying elements in applications like structures of turbine and aerospace sectors [25]. Epoxy resin reinforced with silk was used as a composite in the form of square tube energy-absorbers to check the crashworthiness of passenger vehicles [26]. The composites were found to be useful in energy absorbing applications. Figure 9 represents the use of silk fibers in making fabrics.

Since silk fibre is having superior resistance against fatigue, the composite involving silk fibers can reduce the propagation of the crack. Silk fibers have made bowstrings, fishing nets and wound dressings. Silk fibers exhibit piezoelectric behaviour and hence could also be used as potential candidates for preparing devices in optical fields.

2.8 *Banana Fibre-Reinforced Composite*

Banana fibers mixed with polyvinyl alcohol composite films were suggested as a food packaging material since the swelling of the films reduced with the increasing content of banana fiber in the blend [27]. Ramesh et al. [28] highlighted the importance of the synthesized banana fiber and epoxy resin-based composite as a substitute for fibre-reinforced polymer matrix composites since the natural fiber composite was able to endure higher loads. Researchers have opined the application of banana and cotton fibre-based composite in manufacturing of materials requiring lesser strengths. Banana fibers reinforced in polymer matrix could be satisfactorily used in building applications [29]. Venkateshwaran et al. [30] reported the potential application of banana fibre-based polymer composite in automotive and machinery fields since the fibers considered possessed high tensile modulus, relatively low density, and high tensile strength.

Banana fibers have been used in the manufacturing of ropes. Since it has natural buoyancy, the fiber can be effectively used in the preparation of shipping cables. The other desirable property of the fiber is its resistance towards seawater. Fishing nets, decorative papers, cordage, cables in wall drilling operations and wall furnishings also use banana fibers. Postcards, socks, note books, paper boards and tea bags are few other applications of banana fibers [31].

Soybean associated polyester and epoxy matrix reinforced with banana fibers have potential applications in transportation and automotive fields [31]. Hockey equipment was another potential application of banana fibre-related hybrid composites that effectively endured higher loads and could substitute the glass fibre-based composites [32]. Fibers of banana are used in the preparation of medium weight and lightweight composites. The composites are apt for agro-based industries.

2.9 Bamboo Fiber-Fortified Composite

Bamboo based composites are extensively used in designing interiors involving panels and furniture. Their use is limited in automotive fields, but they are found to have potential applications in structural and aerospace applications. Composites with bamboo can be used in making ply bamboo and medium density boards. Bamboo based composites have been found to have applications in the aircraft and vehicle interiors; helmets used by bicyclists and decks prepared for leisure activities are some other examples where the composites are widely used [33]. Bamboo fibre-reinforced in resin have also got probable applications in architectural fields [34].

Wood interiors were replaced with bamboo-based composite owing to the strength of bamboo and found to be ten times stronger than materials made up of wood. The other desirable properties of the composite were low flame speed, low maintenance and longevity.

The car-like dashboard, door panels, floor mats and cloth seats were also manufactured using bamboo composites. Spring chairs and stools as other applications of the said composite in furniture [35]. Figure 10 depicts the use of bamboo fiber in making door panels.

Fig. 10 Bamboo fibre applications

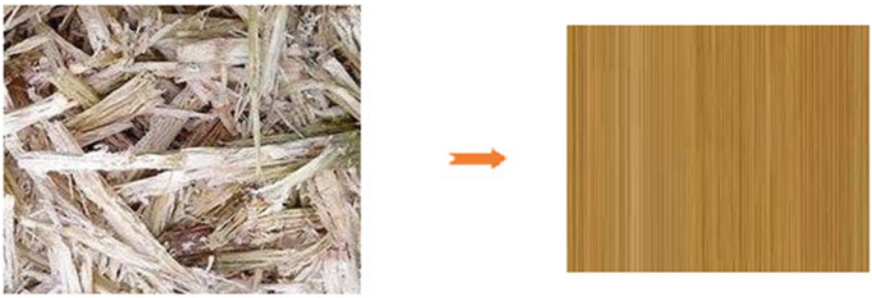


Fig. 11 Bagasse fibre applications

2.10 Bagasse Fibre-Strengthened Composite

Sugar cane bagasse is primarily used in fuels, enzymes and feedstocks. Bagasse is known to have low densities, and hence, structures of low weight, false ceilings, particle boards are some applications where bagasse fibers are used as reinforcement materials. Bagasse of sugarcane, oil palm and phenol–formaldehyde hybrid composites were prepared for making thermal insulation boards.

The other applications were in the construction field involving the preparation of cement panels using carbon nanotubes and fibers of sugar cane bagasse. The flexural strength of the panels was found to have higher flexural strength when compared with unreinforced cement panels. Panels of bagasse-based composites were found to have potential applications in lightweight structures due to the economic benefits [36]. Xiong [37] observed the competitive advantages of composites involving bagasse that do not require high mechanical properties like sound insulators. Composites synthesized through bagasse could be used as conductive materials for applications in the packaging industry. Heavy metals could also be absorbed by using composites prepared through bagasse.

Anti-static and anti-bacterial material in packing applications is some potential applications of conductive composites synthesized using polyaniline conducting polymer and bagasse. The process involved using dodecylbenzene sulfonic acid and ammonium persulfate during polymerization [38]. Figure 11 represents the use of bagasse in making thin sheets.

2.11 Cotton Fibre-Reinforced Composites

Cotton fibers are known for its absorbency and ability to blend effortlessly with any fiber. They offer superior strength with durability. In thermo-acoustic insulations, polymer composites reinforced with insulating cotton fibers are widely used.

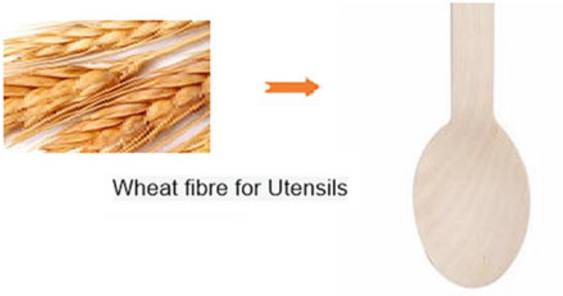


Fig. 12 Wheat fibre applications

Recently, they have found potential applications in the automotive industries owing to their inherent strength. Cotton fibre-reinforced polyester composites were used as bearings involved with water cooling [39].

Unsaturated polyester and cotton fiber composite was suggested for packaging applications due to their improved mechanical properties compared with coir and cotton-based unsaturated polyester composite [40]. Composite plates prepared from polyester-based resin and cotton fibers were investigated for use in structural parts like panels and doors and found satisfactory [41].

2.12 Wheat Fiber Strengthened Composite

Elmessiry and Deeb [42] prepared wheat straw composite with resin and protein colloid blues for applications in the flat board while hybrid composites involving wheat straw and flax fibers were opted for potential applications as shafts having round cross-sections. In Fig. 12, wheat fibre application is illustrated.

Further, wheat straw modified with caprolactam and polyethylene were used to prepare composites using melt blend technique. The composites offered higher mechanical properties since the modified wheat straw was found to have more excellent compatibility with the polyethylene. The modified wheat fibres would function as "biological steel" while forming bio composites [43].

2.13 Abaca Fibre-Reinforced Composite

Abaca fibers is regarded as one of the strongest available natural fibers. Presently, it is used in ropes and twines. The fibre-reinforced composite material could have potential applications in the airframe of crewless aerial vehicle. The fibre is also used in textile industries, handicraft, gift boxes, packaging materials, decorative accessories, wall coverings, foot wear, tea bags, coffee filters, surgical masks, caps and orthopedic materials [44].

The composites used as under floorings in cars had the reinforcement of abaca fibers. Since the fibres had high flexural strengths and exhibited high resistance against rotting, the exterior parts meant for the vehicle could pass the required rigorous necessities related to the vehicle's components [45].

Thermosetting plastic and abaca-based composites prepared through hand lay-up technique were suggested for applications in chemical vessels, tanks and pipes; however, since the fibers are associated with absorption of water, there are few drawbacks of using the composite [46]. If they are suitably addressed, they would have potential applications in the transport field, and the fibres could be selected as possible reinforcement for materials in wind turbines and transport industries [45, 47].

Sinha et al. [48] discussed utilising polypropylene-based abaca fibre composites in industrial and constructional applications; since the composites offered lesser transverse thermal conductivity, they could be used as thermal insulators in refrigeration components.

2.14 *Oil Palm Fibre Reinforced Composites*

Oil palm empty fruit bunch fibers have found applications in plywood and particleboard; oil palm frond fibers have been used in paper, pulp, biodegradable film, downdraft gasifier and fibreboard, while the oil palm trunk fibers have been used for making furniture. Thermoplastics and thermoset based oil palm fibre have extensive applications in the field of automobile components. Components of car-like rear parcel shell, splash shield, bumpers, plastic pellets and spare wheel could be made by technologies offered by Malaysian Palm Oil Board through an extrusion process. Oil palm fibers, when mixed with polyols, could produce lighter weight products like roof insulators and packaging materials [48] as shown in Fig. 13.

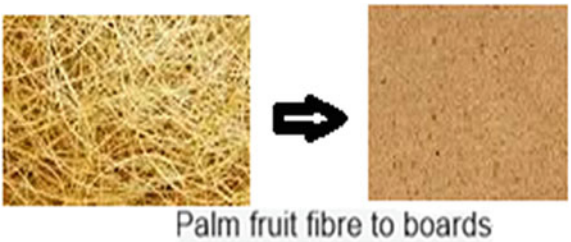


Fig. 13 Palm fibre applications

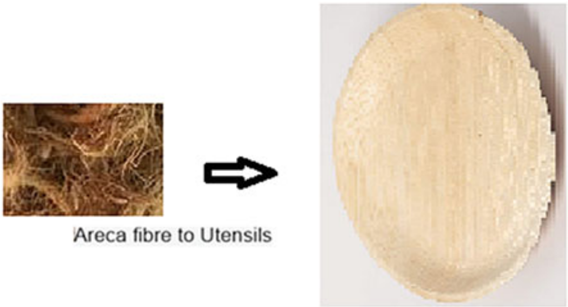


Fig. 14 Areca fibre applications

2.15 Areca Fibre Reinforced Composites

Areca fibers are generally inexpensive and generally found in abundance. The fibres are hard and the cellular structure of the fibers are much similar to coir fibers. The composite is suitable for preparing lightweight materials with potential applications in office furniture, automotive body building and partition panels [49]. Some of the applications of fibre reinforced composites are also found in the field of electrical insulation.

The areca/betel nut fibre reinforced composites finds more significant advantages in the latest development of composite materials such as electrical insulation, automobile bodybuilding and light load applications. The composites that used treated fibers were superior to glass fibre reinforced polyester and had nearly the same mechanical properties as that of the glass-reinforced polyester. In applications related to low-cost housing and packaging, areca fibre with maize powder strengthened composites were found to be useful. The fibre of areca sheath was also used in automobiles' interiors, storage of grains, partition of boards, suitcases, and post-boxes [50]. The laminate prepared by using areca fibre could be used to manufacture items like packaging box and pen stand [51]. The flower pot stand frame was prepared using a combination of areca sheath, jute fibre, glass fabrics, and epoxy resin and had shown lesser deformation [52]. Areca fibers also are used in making utensils (Fig. 14).

2.16 Okra Fibre-Based Composite

Okra fibre reinforced composites could be used in various parts of automobile. The polyester-based composites with okra fibre have insulation property, hence finding potential applications in the electrical industry [53, 54].

The bast fibers of okra which contribute to around 10 to 25% of the weight of the plant, are usually strong and comparable to the fibers of hemp and jute. The fibers are generally shiny and bright; the bast fibers from the stem are investigated for their ability to act as load-bearing members in the composites. Since the hybrid composite made from okra fibers have less weight, they are suitable for materials

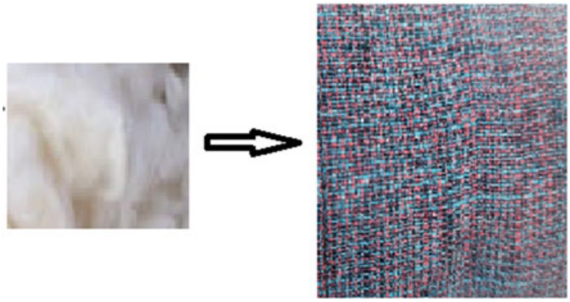


Fig. 15 Kapok fibre application in making fabrics

in architectural and building sectors. Walkway paths, architectural landscaping and panels for partition are few other areas where the composite can be used since they absorb minimum water. The composite has better sound-absorbing efficiency and resistance against shatter when compared to glass fibre reinforced composite. The composite prepared from okra and polylactic acid was able to compost completely after forty days in soil. This may reduce waste associated with construction and help in the sustainability concept [54]. Onyedum et al. [55] investigated banana and okra fibre-based composite in bumpers of automotive cars.

2.17 Kapok Fibre-Reinforced Composites

The kapok fiber happens to be one of the lightest natural fiber available. It is lighter than cotton fiber. It is generally called silk cotton since it lustres similar to silk. Venkata Reddy et al. [56] synthesized polyester-based hybrid composites involving sisal, kapok and glass fabrics and suggested the use of the composites in structural applications like automotive interior parts.

Composite was prepared by Liu et al. [57] using kapok fibre and hollow polyester and evaluated for sound-absorbing properties at low frequencies. In contrast, Lyu et al. [58] used polyε-caprolactone as matrix and kapok fibers as reinforcements and composites were prepared using a suitable flame retardant through hot pressing method. The composite was found to be suitable for applications in building materials. The kapok fibre-based polyester composites were found to be resistant to chemical attacks [59]. In Fig. 15, kapok fibre application is represented.

2.18 Milkweed Fibre-Reinforced Composites

The stem of the milkweed plant is often used for making natural rubber, while the seeds could be used to manufacture oil. The fiber had potential applications in the field of textiles. The milkweed floss has been used as filling material in jackets due to a completely hollow center. Due to the milkweed floss's low density, the composites reinforced with milkweed floss were preferable for developing light weight composites [60]. The fibers of the milkweed plant could be used for reinforcing cement-based composite structures. A higher amount of fibers per unit weight could be added due to the low density of fibers, thus aiding in manufacturing composite structures with lightweight is explained [61].

2.19 Pineapple Leaf Fiber Composites

Pineapple leaf fiber is generally white in colour and is smooth. The fiber is of medium length and possess high tensile strength. The fiber is also known to have higher stiffness, but it is hydrophilic due to the higher content of cellulose. Due to the incredible mechanical properties of fibers, they could be used in preparing polymer composites, biodegradable plastic composites and low-density polyethylene composites.

The fibers are abundantly used in industrial applications due to the ease of availability. Threads are made from these fibers for textile fabrics. Baggage, cabinets, sports item, automobiles and mats are a few other areas where the fibers are used. The belt, transmission cloth, conveyor belt cord, airbag tying cords, and transmission cloth are other machinery parts prepared using palm leaf fibers subjected to surface modification. Biopolymer's coating, cosmetics and medicine are few other applications of using the fiber [62]. Jamaluddin et al. [63] studied the effect of addition of palm leaf fiber in tapioca biopolymer and opined about its potential application as a renewable and biodegradable polymer.

2.20 Nettle Fibre-Reinforced Composites

Nettle is an herbaceous plant of the Urticaceae family. The entire plant could be used for various purposes like medicine, textile production, fodder, cosmetic and medicine [64]. Fiber from nettle plant is used in producing threads and ropes, while the leaves are used as vegetables. Sandeep Kumar et al. [65] worked on epoxy-based bauhinia vahlii and nettle fibre-reinforced composite and concluded that they could be used in products subjected to moderate tribological resistance. The composite could also be used in products having reasonable mechanical strength.

Nataraj et al. [66] investigated on dynamic and mechanical properties of nettle based polyester composites to check for the appropriateness of the synthesized composite for structural applications like machine tools. Since the machine tools operate at high speeds, high damping is preferred. The synthesized composites had offered good damping ratio. The composite could be used in potential applications involving automobile and aerospace applications.

The fiber was considered for applications in gear wheels, dashboard panels of automotive/aircraft. The nettle-based composites were suggested for applications in machine tool structures like micro lathe bed [67].

2.21 Elephant Grass Fibre-Reinforced Composites

Elephant grass is yellowish in colour and generally grows in dense clumps in rich soil. Studies were carried out to find the potential application of grass in the production of biogas. Polyester resin reinforced with elephant grass was used to prepare composite through hand layup technique. Since the density of the grass fiber was less, the fibers find potential applications for making light weight structures [68].

Ramaiah et al. [69] synthesized composite using elephant grass fiber and polyester resin using hand lay-up technique. The processed composites were found to be light in weight and had good thermal insulating properties. Further, on comparing with pure resin, the thermal conductivity and specific heat capacity of the glass fibre-reinforced composite was always less. They were also economical; they could be used in air-conditioners, interior parts of automobiles and electronic packages.

2.22 Luffa Fibre-Reinforced Composites

Luffa cylindrica, also known as luffa sponge, is known to have potential applications in packaging, sound absorption, and vibration isolation. The fibers of luffa possess good sound absorption coefficient and hence exhibit better acoustic properties. The fruit can be used in making composite materials since it is able to offer decent adhesion with the matrix due to its surface morphology. Luffa based natural composites could be used in cars, airplanes and yachts due to their ability to isolate vibrations and sound. Numerous researches had also projected using the luffa-based composites in printed circuit boards and building applications [70]. Doors, fiberboard and house panels were also some potential applications of luffa fiber composites [71]. Figure 16 shows luffa fibers.

2.23 Rice Fibre-Reinforced Composites

Rice husks are agricultural residues that are available in huge quantities during the milling process of rice. In rural areas, it is used as a fuel. However, in the recent times, composites were manufactured from agricultural wastes like rice husk. The ash obtained from rice husk was mixed with cement to produce cement-based composite.

Recycled polypropylene pellets and rice husk-based composites were formed in filaments for 3D printing applications by Maria et al. [72]. Automotive bumper was

Fig. 16 Luffa fibre

Fig. 17 Rice husk fibre applications

manufactured by using epoxy-based rice straw fiber composite through filament winding method [73]. In Fig. 17, the rice husk fibre application in automobile application is represented. Composites manufactured with rice husk could be used as substitute for wood. If the rice husk is properly blended with polymers, they could be used for manufacturing plastic toys [74].

2.24 Roselle (Hibiscus Sabdariffa) Fibre-Based Composites

Hibiscus sabdariffa is a shrub pertaining to Malvaceae family. Fibers obtained from the stem were examined for applications in particle boards, textile industries, paper products and composite materials [75]. In Fig. 18, one of the roselle fibre application is represented. Karakoti et al. [76] opined that the fiber from the plant could be used in the manufacturing of polymer-based composite, particularly in light weight applications like sports goods, panels relating to interiors of automobiles and biomedical fields.

Fig. 18 Roselle fibre applications

Fig. 19 Maize fibre applications

2.25 Maize Fibre-Reinforced Composites

Maize (Corn) is a staple food in different parts of the world. Corn fiber is a byproduct of the corn wet-milling industry. N H Sari and S Suteja [77] prepared Cornhusk fibre reinforced polyester resin composites and communicated about its application in exterior windows, decking, siding, and doors. Modified maize stalk fibers were used as reinforcements in natural rubber and revealed about its possible use in the production of shoe sole [78]. The application of maize fiber in fabric is shown in Fig. 19.

3 Challenges in Using Natural Fibers

Natural fibers used in composites are found to absorb water and offer weak interfacial adhesion with polymer matrix. They are subjected to degradation when exposed to the external environment through mechanical, biological and fire means. Organisms might attack cellulose and convert to digestible units. Hence, the interface between the fibers and matrix will weaken and offer lesser strength in composites. Sometimes, oxidation and reduction reactions occur through enzymes.

Degradation due to water is a major challenge with the natural fibre-based composites since they are found to be hydrophilic. They are easily able to absorb water in the external environment due to ice, sea and sources like dew. Swelling is seen in the reinforced composites when the fibers absorb water due to the presence of hemicelluloses. However, it is also observed that the composites also shrink when they dry up. The interface between the fiber and matrix weakens when the fibers tend to absorb water due to the presence of hydroxyl groups. Ultraviolet radiations degrade fibers when lignin content present in the fiber is exposed to radiations. Wind, snow and dust also degrade the composite through the formation of cracks through mechanical means. Resistance against fire is also found to be poor when the composites are used for structural applications. Due to the thermal degradation, change of odour and colour is also noticed in the biofibre reinforced composites [79].

4 Conclusion

Considering the challenges in processing bio fiber composites, surface modification is effectively carried out to improve fibre surface properties, and researchers have successfully improved the compatibility between the fiber and matrix. Several properties that were once considered as challenging were improved during the modification of fibers. Silane treatment was used to modify some of the natural fibers and could effectively enhance the strength and Youngs modulus of the fibers. In order to reduce the absorption water, coupling agents were used during the synthesis of the above said composites. For processing natural fibers, enzyme technology is used significantly since it is considered to be environment friendly and cost-effective.

One of the exceptional features of synthesizing bio fibre-reinforced composites is due to the fact that the mechanical properties could be custom made to such an extent that it would rightly suit a specific application. The fiber orientation and placement could be changed easily to exhibit either highly anisotropic or isotropic property based on the end application.

As discussed earlier, natural fibers have been considered a substitute for non-recyclable fibers since they are renewable, cheap, and easily recyclable. The other advantages of using natural fibers would be owing to its high toughness, low densities and CO_2 neutrality.

Further, the expense incurred in processing a bio fibre-based composite is quite less compared to conventional materials used. The longing for making green products is one more reason to deliberate on using the bio fibre-based composites in almost all fields of engineering. The day-to-day improvements in technology related to synthesizing bio fibre-based composites will also lead to improved product and material features. The composites would become further diverse and venture markets that were once considered unexplored and could be used in almost all fields of engineering.

References

1. Zhang L, Hu Y (2014) Novel lignocellulosic hybrid particleboard composites made from rice straws and coir fibers. Mater Des 55:19–26
2. Speaking R, Jawaid M, Ariffin H, Salit MS (2018) Effects of surface treatments on tensile, thermal and fibre-matrix bond strength of coir and pineapple leaf fibres with polylactic acid. J Bionic Eng 15(6):1035–1046

3. Andiç-Çakir O, Sarikanat M, Tüfekçi HB, Demirci C, Erdogan ÜH (2014) Physical and mechanical properties of randomly oriented coir fiber–cementitious composites. Compos B Eng 61:49–54
4. Sakthivel M, Ramesh S (2013) Mechanical properties of natural fiber (banana, coir, sisal) polymer composites. Sci Park 1(1):1–6
5. Dong Y, Ghataura A, Takagi H, Haroosh HJ, Nakagaito AN, Lau K-T (2014) Polylactic acid (PLA) biocomposites reinforced with coir fibres: evaluation of mechanical performance and multifunctional properties. Compos Appl Sci Manuf 63:76–84
6. Yousif B, Ku H (2012) Suitability of using coir fiber/polymeric composite for the design of liquid storage tanks. Mater Des 36:847–853
7. Ayrilmis N, Jarusombuti S, Fueangvivat V, Bauchongkol P, White RH (2011) Coir fiber reinforced polypropylene composite panel for automotive interior applications. Fibers Polym 12(7):919
8. Rajak DK, Pagar DD, Menezes PL, Linul E (2019) Fiber-reinforced polymer composites: Manufacturing, properties, and applications. Polymers 11(10):1667
9. Arockiam, N.J.; Jawaid, M.; Saba, N. Sustainable biocomposites for aircraft components. In Sustainable Composites for Aerospace Applications; Woodhead Publishing: Sawston, UK; Cambridge, UK, 2018; pp 109–123
10. Akil H, Omar MF, Mazuki AM, Safiee SZ, Ishak ZM, Bakar AA (2011 Sep 1) Kenaf fiber reinforced composites: A review. Mater Des 32(8–9):4107–4121
11. Hassan F, Zulkifli R, Ghazali MJ, Azhari CH (2017) Kenaf fiber composite in automotive industry: an overview. International Journal on Advanced Science, Engineering and Information Technology. 7(1):315–321
12. Du Y, Yan N, Kortschot MT (2015 Jan) The use of ramie fibers as reinforcements in composites. Biofiber Reinforcements in Composite Materials. 1:104–137
13. Netravali A.N. (2004) Ramie Fiber Reinforced Natural Plastics. In: Wallenberger F.T., Weston N.E. (eds) Natural Fibers, Plastics and Composites. Springer, Boston, MA. https://doi.org/10.1007/978-1-4419-9050-1_18
14. Yan L, Chow N, Jayaraman K (2014 Jan) Flax fibre and its composites–A review. Compos B Eng 1(56):296–317
15. Zhu J, Zhu H, Njuguna J, Abhyankar H (2013 Nov) Recent development of flax fibres and their reinforced composites based on different polymeric matrices. Materials 6(11):5171–5198
16. Gopalan V, Suthenthiraveerappa V, Annamalai AR, Manivannan S, Pragasam V, Chinnaiyan P, Mannayee G, Jen C-P (2021) Dynamic Characteristics of Woven Flax/Epoxy Laminated Composite Plate. Polymers 13:209. https://doi.org/10.3390/polym13020209
17. Mohammed L, Ansari MN, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. International Journal of Polymer Science. 2015
18. Gon D, Das K, Paul P, Maity S (2012) Jute composites as wood substitute. International Journal of Textile Science. 1(6):84–93
19. El-Sayed AA, El-Sherbiny MG, Abo-El-Ezz AS, Aggag GA (1995 Apr 1) Friction and wear properties of polymeric composite materials for bearing applications. Wear 184(1):45–53
20. Gopinath A, Kumar MS, Elayaperumal A (2014 Jan) Experimental investigations on mechanical properties of jute fibre-reinforced composites with polyester and epoxy resin matrices. Procedia Engineering. 1(97):2052–2063
21. Swift DG. Sisal-cement composites and their potential for rural Africa. In: Marshall IH, editor. Composite structures 3, Elsevier Applied Science Publisher. London/New York: p. 774–87
22. Medhi A, AitTahar K, Bibi M (2008 Apr 18) Studies of sisal fiber-containing composites. Journal of Natural Fibers. 5(1):36–46
23. de Andrade SF, Zhu D, Mobasher B, Soranakom C, Toledo Filho RD (2010 Jan 15) High speed tensile behavior of sisal fibre-cement composites. Mater Sci Eng, A 527(3):544–552
24. Xin X, Xu CG, Qing LF (2007) Friction properties of sisal fibre reinforced resin brake composites. Wear 262(5–6):736–741
25. Hamidi YK, Yalcinkaya MA, Guloglu GE, Pishvar M, Amirkhosravi M, Altan MC (2018 Nov) Silk as a natural reinforcement: processing and properties of silk/epoxy composite laminates. Materials 11(11):2135

26. Oshkovr SA, Eshkoor RA, Taher ST, Ariffin AK, Azhari CH (2012 Jul 1) Crashworthiness characteristics investigation of silk/epoxy composite square tubes. Compos Struct 94(8):2337–2342
27. Sathasivam K, Mas Haris MR, Noorsal K (2010 Sep 30) The preparation and characterization of esterified banana trunk fibers/poly (vinyl alcohol) blend film. Polym-Plast Technol Eng 49(13):1378–1384
28. Ramesh M, Atreya TS, Aswin US, Eashwar H, Deepa C (2014 Jan) Processing and mechanical property evaluation of banana fiber reinforced polymer composites. Procedia Engineering. 1(97):563–572
29. Pothan LA, Thomas S, Neelakantan NR (1997 May) Short banana fiber reinforced polyester composites: mechanical, failure and aging characteristics. J Reinf Plast Compos 16(8):744–765
30. Venkateshwaran N, Elayaperumal A (2010 Aug) Banana fiber reinforced polymer composites-a review. J Reinf Plast Compos 29(15):2387–2396
31. Vigneswaran C, Pavithra V, Gayathri V, Mythili K. Banana fiber: scope and value-added product development. Journal of Textile and Apparel, Technology and Management. 2015 May 19;9(2).
32. Al Rashid A, Khalid MY, Imran R, Ali U, Koc M (2020 Jan) Utilization of Banana Fiber-Reinforced Hybrid Composites in the Sports Industry. Materials 13(14):3167
33. Shah AU, Sultan MT, Jawaid M, Cardona F, Talib AR (2016 Sep 1) A review on the tensile properties of bamboo fiber reinforced polymer composites. BioResources 11(4):10654–10676
34. Biswas S (2012 Sep) Mechanical properties of bamboo-epoxy composites a structural application. Adv Mater Res 1(3):221
35. Suhail SS, Khalil HA, Nadirah WW, Jawaid M. Bamboo based biocomposites material, design and applications. In Materials science-advanced topics 2013 Jun 10. Intech Open
36. Devadiga DG, Bhat KS, Mahesha GT (2020 Jan 1) Sugarcane bagasse fibre-reinforced composites: Recent advances and applications. Cogent Engineering. 7(1):1823159
37. Xiong W (2018 Aug) Bagasse composites: A review of material preparation, attributes, and affecting factors. J Thermoplast Compos Mater 31(8):1112–1146
38. Youssef AM, El-Samahy MA, Rehim MH (2012 Aug 1) Preparation of conductive paper composites based on natural cellulosic fibers for packaging applications. Carbohyd Polym 89(4):1027–1032
39. - Cotton reinforced polymer composites, Editor(s): Navin Chand, Mohammed Fahim, In Woodhead Publishing Series in Composites Science and Engineering, Tribology of Natural Fiber Polymer Composites, Woodhead Publishing, 2008, Pages 129–161, ISBN 9781845693930, https://doi.org/10.1533/9781845695057.129
40. Balaji V (2017) Mechanical characterization of coir fiber and cotton fibre-reinforced unsaturated polyester composites for packaging applications. Journal of Applied Packaging Research. 9(2):2
41. Raftoyiannis, "Experimental Testing of Composite Panels Reinforced with Cotton Fibers," Open Journal of Composite Materials, Vol. 2 No. 2, 2012, pp. 31–39. https://doi.org/10.4236/ojcm.2012.22005
42. Elmessiry M, Deeb E (2016) Analysis of the wheat straw/flax fibre-reinforced polymer hybrid composites. J. App. Mech. Eng. 5:1–5
43. Zhang W, Chen J, Bekele LD, Liu Y, Duns GJ, Jin L (2016 Apr 4) Physical and mechanical properties of modified wheat straw-filled polyethylene composites. BioResources 11(2):4472–4484
44. Punyamurthy R, Sampathkumar D, Bennehalli B, Gouda RP, Srinivasa CV (2015 Jun 1) Influence of fiber content and effect of chemical pre-treatments on mechanical characterization of natural abaca epoxy composites. Indian J Sci Technol 8(11):53236
45. Delano JA (2018 Dec 2) A review on abaca fibre-reinforced composites. Compos Interfaces 25(12):1039–1066
46. Tumolva TP, Kubouchi M, Aoki S. Development of furan-based green composites. Proceedings of the international committee on composite materials (ICCM17); 2009 July 27–31; Edinburgh, Scotland.

47. Sinha AK, Bhattacharya S, Narang HK (2020 Nov) Abaca fibre reinforced polymer composites: a review. J Mater Sci 25:1–9
48. Abdul Khalil HPS, Jawaid M, Hassan A, Paridah MT, A. Zaidon (August 22nd, 2012) Oil Palm Biomass Fibres and Recent Advancement in Oil Palm Biomass Fibres Based Hybrid Biocomposites. Composites and Their Applications, Ning Hu, IntechOpen,. https://doi.org/10.5772/48235
49. Venkateshappa SC, Bennehalli B, Kenchappa MG, Ranganagowda RP (2010 Jul 15) Flexural behaviour of areca fibers composites. BioResources 5(3):1846–1858
50. Ashok RB, Srinivasa CV, Basavaraju B (2018 May 1) A review on the mechanical properties of areca fibre-reinforced composites. Science and Technology of Materials. 30(2):120–130
51. Heckadka SS, Kini MV, Ballambat RP, Beloor SS, Udupi SR, Kini UA (2014 Nov) Flexural strength analysis of starch-based biodegradable composite using areca frond fibre reinforcement. International Journal of Manufacturing Engineering. 13:2014
52. Jothibasu S, Mohanamurugan S, Vijay R, Lenin Singaravelu D, Vinod A, Sanjay MR (2020 Mar) Investigation on the mechanical behavior of areca sheath fibers/jute fibers/glass fabrics reinforced hybrid composite for light weight applications. J Ind Text 49(8):1036–1060
53. Srinivasababu N (2015) An overview of okra fibre reinforced polymer composites. IOP Conf Ser 626 Mater Sci Eng 83:012003. doi:https://doi.org/10.1088/1757-899X/83/1/012003
54. Khan GM, Yilmaz ND, Yilmaz K. Okra fibers: Potential material for green biocomposites. In Green biocomposites 2017 (pp. 261–284). Springer, Cham.
55. Onyedum O, Aduloju SC, Sheidu SO, Metu CS, Owolabi OB (2015) Comparative mechanical analysis of okra fiber and banana fiber composite used in manufacturing automotive car bumpers. American Journal of Engineering, Technology and Society. 2(6):193–199
56. Venkata Reddy G, Venkata Naidu S, Shobha RT (2008 Nov) Impact properties of kapok based unsaturated polyester hybrid composites. J Reinf Plast Compos 27(16–17):1789–1804
57. Liu X, Yan X, Li L, Zhang H (2015 Jul 4) Sound-absorption properties of kapok fiber nonwoven fabrics at low frequency. Journal of Natural Fibers. 12(4):311–322
58. Liu L, Tian Y, Lu J, Xiong X, Guo J (2020 Jan) Flame-Retardant and Sound-Absorption Properties of Composites Based on Kapok Fiber. Materials 13(12):2845
59. Mahesha GT, Subrahmanya BK, Padmaraja NH. Biodegradable natural fibre-reinforced polymer matrix composites: Technical updates. AIP Conference Proceedings 2019 Oct 25 (Vol. 2166, No. 1, p. 020001). AIP Publishing LLC.
60. Reddy N, Yang Y (2010) Non-traditional lightweight polypropylene composites reinforced with milkweed floss. Polym Int 59(7):884–890. https://doi.org/10.1002/pi.2798
61. Hassanzadeh S, Hasani H (2017 Feb) A review on milkweed fiber properties as a high-potential raw material in textile applications. J Ind Text 46(6):1412–1436
62. Asim M, Abdan K, Jawaid M, Nasir M, Dashtizadeh Z, Ishak MR, Hoque ME (2015 May) A review on pineapple leaves fibre and its composites. International Journal of Polymer Science. 6:2015
63. Jaafar J, Siregar JP, Oumer AN, Hamdan MH, Tezara C, Salit MS (2018 Jul 5) Experimental investigation on performance of short pineapple leaf fiber reinforced tapioca biopolymer composites. BioResources 13(3):6341–6355
64. Bedros E, Baley C. Investigation of the use of stinging nettle fibres (UrticaDioica) for polymer reinforcement: Study of single fibre tensile properties. In13th European Conference on Composite Materials 2008 Jun 2.
65. Kumar S, Mer KK, Gangil B, Patel VK (2020 Aug 1) Synergistic effect of hybrid Himalayan Nettle/Bauhinia-vahlii fibers on physico-mechanical and sliding wear properties of epoxy composites. Defence Technology. 16(4):762–776
66. Mahendra Kumar N, Thyla PR, Mohanram PV, Sabareeswaran A, Manas RB, Srivatsan S (2015 Dec 1) Mechanical and dynamic properties of nettle-polyester composite. Mater Express 5(6):505–517
67. Pokhriyal M, Prasad L, Rakesh PK, Raturi HP (2018 Jan 1) Influence of fiber loading on physical and mechanical properties of Himalayan nettle fabric reinforced polyester composite. Materials Today: Proceedings. 5(9):16973–16982

68. Rao KM, Prasad AR, Babu MR, Rao KM, Gupta AV (2007 May) Tensile properties of elephant grass fiber reinforced polyester composites. J Mater Sci 42(9):3266–3272
69. Ramaiah K, Prasad AR, Reddy KH (2012 Dec) Thermophysical properties of elephant grass fiber-reinforced polyester composites. Mater Lett 15(89):156–158
70. Alhijazi M, Safaei B, Zeeshan Q, Ismael M, Eyvazian A, Qin Z (2020 Jan) Recent Developments in Luffa Natural Fiber Composites. Sustainability 12(18):7683
71. Parida C, Dash SK, Das SC. Effect of fiber treatment and fiber loading on mechanical properties of luffa-resorcinol composites. Indian Journal of Materials Science. 2015;2015.
72. Morales MA, Atencio Martinez CL, Maranon A, Hernandez C, Michaud V, Porras A (2021 Jan) Development and Characterization of Rice Husk and Recycled Polypropylene Composite Filaments for 3D Printing. Polymers 13(7):1067
73. Saidah A, Susilowati SE. Design of composite material of rice straw fiber reinforced epoxy for automotive bumper. In2017 International Conference on Computing, Engineering, and Design (ICCED) 2017 Nov 23 (pp. 1–4). IEEE.
74. Bisht N, Gope PC, Rani N (2020 Dec 9) Rice husk as a fibre in composites: A review. J Mech Behav Mater 29(1):147–162
75. Akubueze EU, Ezeanyanaso CS, Muniru OS, Nwaeche FC, Tumbi MI, Igwe CC, Elemo GN (2019 Feb) Extraction and characterization of bastFibres from Roselle (Hibiscus Sabdariffa) stem for industrial application. Journal of Materials Science Research and Reviews. 9:1–7
76. Karakoti A, Biswas S, Aseer JR, Sindhu N, Sanjay MR. Characterization of microfiber isolated from Hibiscus sabdariffa var. altissima fiber by steam explosion. Journal of Natural Fibers. 2018 May 22.
77. Sari NH, Suteja S. Corn husk Fibers Reinforced Polyester Composites: Tensile Strength Properties, Water Absorption Behavior, and Morphology. In IOP Conference Series: Materials Science and Engineering 2020 (Vol. 722, No. 1, p. 012035). IOP Publishing.
78. Chigondo F, Shoko P, Nyamunda BC, Moyo M (2013) Maize stalk as reinforcement in natural rubber composites. Int J Sci Technol Res 2(6):263–271
79. Kumar R, Ul Haq MI, Raina A, Anand A (2019) Industrial applications of natural fibre-reinforced polymer composites–challenges and opportunities. Int J Sustain Eng 12(3):212–220

Biodegradable Fibers, Polymers, Composites and Its Biodegradability, Processing and Testing Methods

Magdi EL Messiry

Abstract The worldwide awareness of the environment urged the search for new composites based on bio fibres. As a result, the focus shifted back to natural fibres, which are biodegradable and typically less expensive than synthetic fibres.Besides, there exists a huge amount of agricultural waste suitable to be used as bio fibre composite materials. Such composites find a wide application, for instance in the automotive industry, structural components, panels, noise control, acoustic wall, agro-fibres biocomposites, wind turbine blades, and many more. Synthetic polymers or eco-friendly polymers, such as poly(glycolic acid), poly(lactic acid), and their copolymers—poly(lactic-co-glycolide) or poly(l-lactic acid), polydioxanone, and poly(l-lactic acid), can be used to strengthen these fibres (caprolactone).The choice of both components' biodegradable in the bio-composites becomes crucial from the environmental perspective. This chapter covers a wide range of topics, including data on fibre/polymer composites and/or bio-composites, as well as the design of fibre composites. Also, this chapter reviews the natural fibre/reinforced polymers (NFRPs) degradability.

Keywords Biodegradable polymer · Structural designs · Bio-composites · Poly(lactic acid) (PLA)

Abbreviations

PLA	Poly(lactic acid),
PHAs	Polyhydroxyalkanoates,
PHB	Polyhydroxybutyrate,
PHBV	Poly(hydroxybutyrate-co-hydroxyvalerate),
PCL	Polycaprolactone,
PBAT	Poly(butylene adipate-co-terephthalate),

M. EL Messiry (✉)
Textile Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_5

PBS	Poly(butylene succinate),
PE	Polyethylene,
PP	Polypropylene,
PET	Poly(ethylene terephthalate),
PEG	Poly(ethylene glycol),
NR	Natural rubber,
LCP	Liquid crystal polymer,
LDPE	Low density polyethylene,
LLDPE	Linear low density polyethylene,
HDPE	High density polyethylene,
HMWHDPE	High molecular weight high density polyethylene,
MBS	Methacrylate-butadiene-styrene terpolymer,
PVC	Polyvinyl chloride,
TPU	Thermoplastic polyurethane

1 Introduction

The bioeconomy is defined as the activity related to the design of biodegradable material using biological resources materials and it has been adopted widely in USA, EU, and Canada [1]. Bioeconomy is needed for the low carbon economy worldwide. The current bioeconomy market has been estimated at € 2.4 billion [2]. Biocomposites are used in numerous industries to produce variety of items, such as construction materials, sporting goods, and consumer electronics. The advantage of the biodegradable composite may be summarized as [3–7]:

- using renewable biodegradable sources,
- low energy consumption,
- cheaper production composite,
- reasonable specific strength and specific elastic modulus,
- availability in many countries across the globe,
- biodegradable product recycling is possible,
- reuse of agricultural waste,
- recycle natural fibre products.

Many countries have instituted laws to promote recycling and turned out into green products [3] in several applications such as various civil engineering locations including roofing and bridges, thin sheets, shingles, roof tiles, prefabricated shapes, panels, curtain walls, precast elements. Cement bonded wood fibre formed from wood fibres in cement matrix is used for the manufacturing of panel sheet bricks as thermal isolators [8–16]. Table 1 gives some products of fibre/polymer composites. The global natural fibre composites market size, valued at US$, will reach about 8 billion [17, 18]. The fibres considered are wood, cotton, flax, hemp. Wood composites are the most popular, followed by cotton, flax, and kenaf fibre. The fibres used

Table 1 Natural fibre/polymer composite applications [3, 10–17]

Product	Reinforcement	Applications	Product	Reinforcement	Applications
Fibre boards	Non-woven, fabrics	Automotive interiors, furniture	Granulate of natural fibres blended with thermoplastic resin	Natural granulated fibres	Pallets, packages, appliances,
3-D shaped fibre boards	Natural fibres, non-woven mats	Automotive interiors, furniture	Boards	Agriculture residues	Furniture, panels, electric wire
Medium density fibreboard (MDF)	Bagasse mixed with other agricultural fibres	Solid wood replacement	Boards	Mix of natural fiber and glass fibres	Boats, water containers, storage grains, etc
Pultrusion profiles	Natural fibres fabrics	Different profiles	Roof shingles	Natural fibres bundles, Non-woven mats	Civil engineering applications
Long fibre reinforced thermoplastic	Natural fibres, roving or yarns	Different profiles as replacement for solid wood	Cellular Concrete	Rice, sisal, jute, sugarcane bagasse, ramie residues	Interiors in high buildings for weight reduction
Molded products	Nonwoven mat	Door siding, automotive industry, panels			

may be in the form of loose fibres, granulated natural fibres, natural fibres bundles, woven fabric, nonwoven fabric, and other forms of fibrous assembly. The natural fibre/polymer composite (NFPC) that can be made from fibres in different forms, yarns, woven or nonwoven, knitted, braided fabrics, is used as reinforcing to form the three-dimensional structure of the composite. The matrix is a polymer that gives the final rigid form of the composite and protects fibres from the surrounding environment. The purpose of the matrix is to keep the fibrous structure in final form through adhere the fibres together and redistribute the applied stress on the fibrous structure so that the applied stress is supported by all fibres in the composite cross-section [5, 19, 20]. Furthermore, a large amount of agricultural waste can be used to make acceptable biodegradable composites [3, 18]. For example, agricultural waste from wheat and rice straw amounts to roughly 710 million metric tonnes and 670 million tonnes, respectively, per year [3, 24–27].

Agriculture and forestry produce 11.9 billion tonnes of dry matter each year, with agriculture producing 61% and forestry producing 39% [28–33]. This is besides the recycled waste of the textile garment (In USA 16.9 million tons, 11.15 million tons were landfills). According to Nova-Institute [34, 35], demand for bio-composite board materials would increase at an ascending rate. Figure 1 demonstrates the

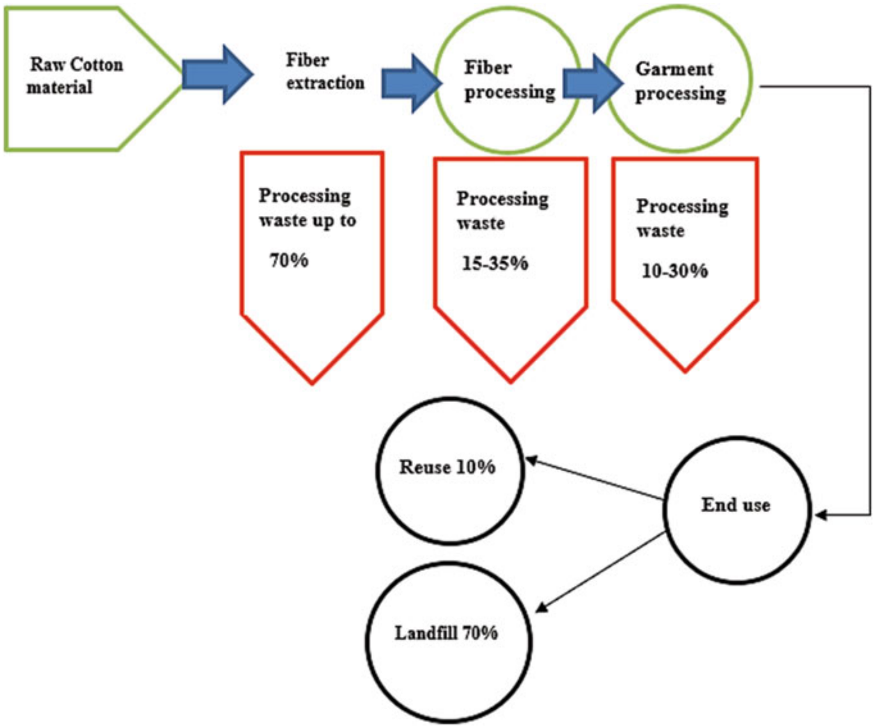


Fig. 1 Distribution of material flow in the cotton production chain

approximate percentage of the waste extracting during the life cycle of cotton fibres, which indicates most of the fibres will be landfilled.

2 Biodegradable Composite

The principle of the circular economy has gained great attention in the last decades, and environmental protection changes the scenarios of the material used for the formation of the different parts constructions, replacing the metal materials with composite materials, and further progress to use biodegradable composites. Replacing manmade fibre decreases the environmental impact of composite materials. The BioSource materials and biodegradable polymers as an alternative to traditional synthetic polymers will result in the biodegradable composite. The choice of both matrix and fibres being biodegradable results in biocomposites.

2.1 Biocomposite Reinforcements

The composite may be constructed in various shapes from the different types of fibres, either in 2-D or 3-D structures.

- Fibre-reinforced polymer
  (short or continuous filament),
- Yarns reinforced polymer
  (spun or multifilament),
- 2-D fabric reinforced polymer
  (woven or nonwoven fabrics),
- 3-D fabric reinforced polymer,
- Particle reinforced polymer
  (whisker, microparticles, or shopped fibres).

The construction of biocomposites can be classified depending on the shape of the material and the layout in the composite as well as the number of layers, single layer, or multi-layer, and finally, the orientation of the fibres in the different layers, Fig. 2.

3 Biodegradable Natural Fibrous Materials

Biodegradable composite is the combination of the biodegradability of the natural fibrous materials when combined with biodegradable polymers or natural resins to form a composite material.Several species of plants can produce fibres from its different parts, for instance from the stem: Jute, Flax, Ramie, Kenaf, leaves; from palm: Sisal, Banana, Abaca, or Cotton. Textile reinforcement for composites totalled $4.3 billion in 2018, with an annual average of 3.3% [5, 36]. Natural fibres are assortedas:

- **Cellulosic**.
  Seed: Cotton, Kapok.
  Stem: Flax, Hemp, Jute, Kenaf, Ramie.
  Leaf: Manella, Sisal, Banana, Abaca, Agave, Pineapple, Palm.
  Fruit: Coir.
  Wood: Hardwood, Softwood.
  Stalk: Rice, Wheat, Barley, Maize, Oat, Rye.
  Grass: Bamboo, Bagasse, Corn, Esparto, Canary, Rice.

- **Protein**.
  Hair: Wool, Alpaca, Camel, Cashmere.
  Secreted by the gland: Silk, Spider silk.

Bast fibres are environmentally friendly and can replace glass fibres in forming good biodegradable composites [3]. The world production of the bast fibres according

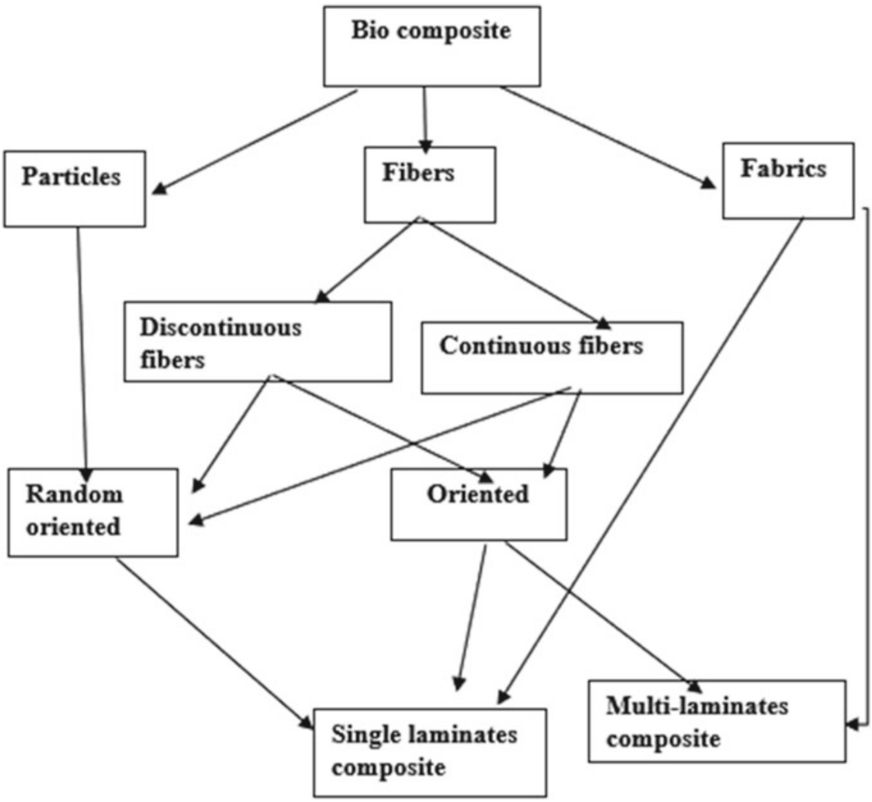


Fig. 2 Classification of biocomposites construction

to the different species is given in Fig. 3. Cotton fibres represent the highest production; it reaches 25 million tons while the bast fibres approximately 4 million tons [1, 29]. Bamboo fibres may reach 30 million tons [37].

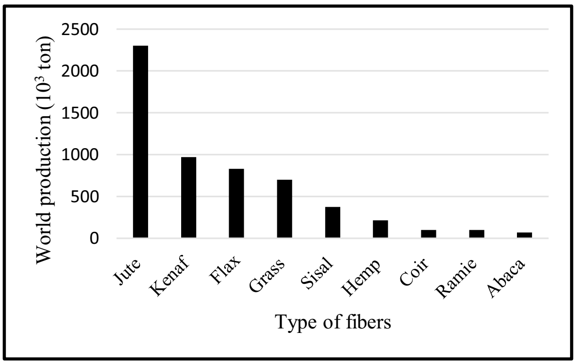


Fig. 3 Bast fibres world production [by the author]

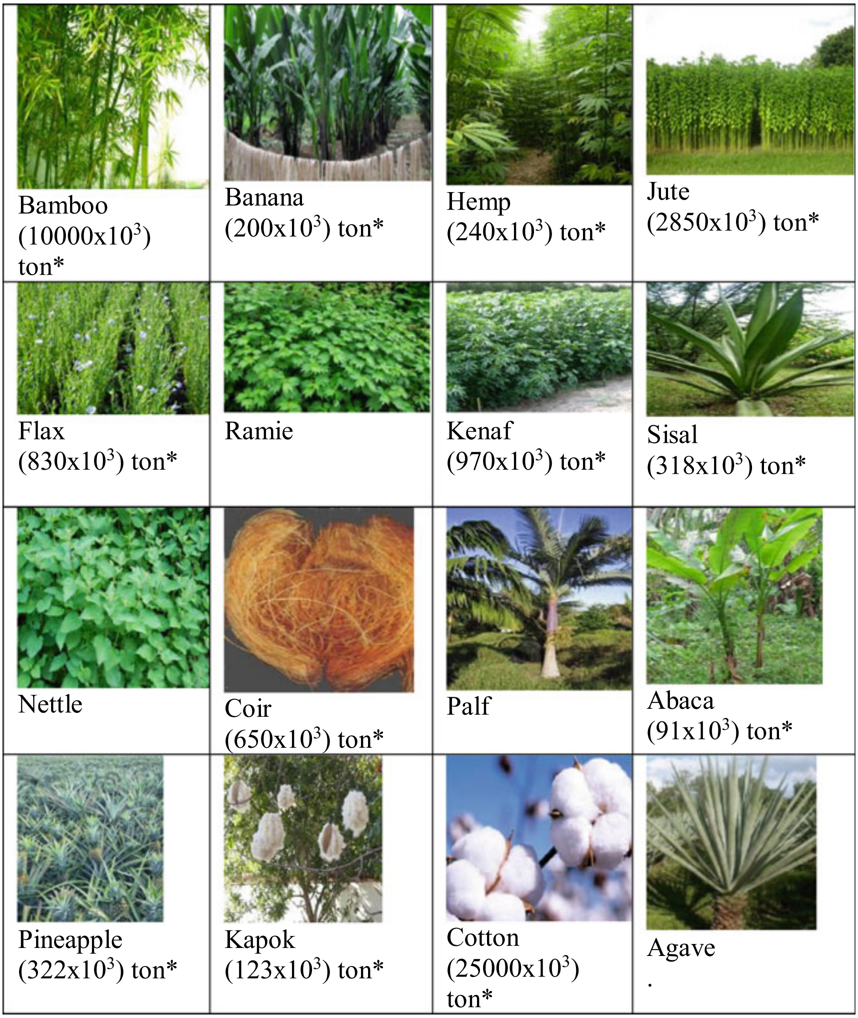


Fig. 4 Examples of different sources of natural biodegradable fibres [30–46]. * World annual production

Figure 4 shows examples of the different sources of natural biodegradable fibres [38–54].

3.1 Biodegradable Fibres Properties

Some Biodegradable fibres properties are provided in Table 2.

Table 3 provides the mechanical properties of the most used fibres for composite manufacturing, which vary greatly according to the source of the fibre's species and where it was cultivated.

Table 2 Fibres physical properties [3, 55–59]

Type of Fibre	Fibre length mm	Average fibre diameter mm	Density g/cm^3	Cellulose content %
Flax	33	0.019	1.45	75
Hemp	25	0.025	1.48	68.5
Jute	3.5	0.020	1.4	55
Kenaf	2–6	0.02	1.29	51
Ramie	160	0.06	1.48	73
Sisal	1–5	0.125	1.45	57
Banana	2.84	18.5	1.4	63
Pineapple	3–9	6	1.44	81
Abaca	6.0	0.02	1.5	60
Coir	200	0.48	1.1	30
Cotton	37	0.02	1.4	87.5
Bamboo	800	–	–	35
Soft wood	3.3	–	1.5	42.5
Hard wood	1–2	0.022	0.75	45

Table 3 Fibres mechanical properties [3, 55–59]

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Specific Young's modulus GPa/(g /cm^3)	Strain %
Flax	500	80	41	4.3
Hemp	550	45	30	3
Jute	625	37	27	2.5
Kenaf	550	25	24	2
Ramie	915	23	15	3.4
Sisal	450	15.5	10.5	8
Banana	720	30	22	2
Pineapple	1020	71	50	0.8
Abaca	700	13	9	6
Coir	140	6	5.2	1.1
Cotton	500	8	8.25	7
Oil Palm	330	150	2.7	2.2
Bamboo	575	27	18	3.1
Nettle	590	87	52.8	2.11
Coconut	150	30	27	5

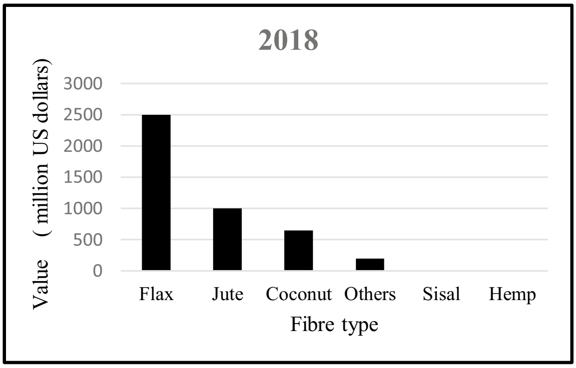


Fig. 5 Value of the world consumption from different natural fibres for manufacturing composite material [60]

The analysis of the different fibres world consumption (not included cotton) is illustrated in Fig. 5 which shows that flax fibres are most consumed.

4 Classification of Biodegradable Polymers

As has been mentioned, the polymer can be a natural material or synthetic, its molecular structure affects physical, mechanical, thermal, and other composite properties [3, 61]. The polymer properties are a result of the mechanical entanglement between chains and forces along with the molecules. Polymer's different properties and its structure define its end-use as well as the biodegradable properties of the biocomposites. The Biofibre composite materialscan be divided into fully biodegradable and partly biodegradable [62], depending on the biodegradability of the matrix that is capable of being decomposed by bacteria or other living organisms. Recently, several biodegradable matrixesare developed [63]. Polylactide acid (PLA), thermoplastic starch, cellulose esters, are examples of the biodegradable polymers from a natural source, while aliphatic polyester, aliphatic–aromatic polyester, polyvinyl alcohol, polyanhydrides, and polyethylene terephthalate are examples of biodegradable polymers from petroleum-based polymers [1]. Partly degradable composites are those using non-degradable polymers, such as polypropylene, polyester, or polyvinyl alcohol.

Natural biodegradable polymers are extracted from biomass or through organically modified organisms [62]. In the last decade, biodegradable polymers, especially PLA, are widely used in the manufacturing of NFPC and other industrial products [64]. Biodegradable polymers are classified:

Agro-polymer: Polysaccharides: starcheswheat, potatoes, maize, lignocellulosic products, wood, straws, chitin, chitosan, gums, alginates.

Bacterial polymers: Semi-synthetic polymers, polyhydroxyalkanoates, Poly (hydroxybutyrate-co-hydroxyvalerate). Microbial polyesters; Poly-3-hydroxyalcanoates, Poly (Hydroxybutyrate-Hydroxyvalerate), Poly (Hydroxybutyrate, Poly- ε-Caprolactones.

Polymers chemically synthesized: Polylactic Acid or Polylactide, Polyglycolic Acid.

In the selection of polymers for each application, some properties are essential for the compatibility of fibre properties, mechanical stresses applied on the composite during services, the suitability for the manufacturing technique of composite formation. The biodegradability of the composite can be tested according to international standards ASTM (D6400 or D6868) for duration of 90 days and up to 180 days, according to standard specifications for compostable plastics. Some other polymer properties are essential for compatibility with the end-use to fulfill matrix performance under various loading conditions, the manufacturing process requirements, and the life cycle analysis of the product.

The polymers can be either natural or synthetic, such as [3, 64]:

Natural

1. Polysaccharides

- Starch
- Cellulose
- Chitin
- Pullulan
- Levan
- Konjac

2. Proteins

- Protein from grains
- Collagen/gelatin
- Casein, albumin, fibrogen, silks, elastin

3. Polyesters

- Polyhydroxyalkanoates, copolymers

4. Other Polymers

- Lignin
- Shellac
- Natural rubber

Synthetic

1. Poly(amides).

2. Poly(anhydrides).

3. Poly(amide-enamines).

4. Poly(vinyl alcohol).

5. Poly(ethylene-co-vinyl alcohol).

6. Poly(vinyl acetate).

7. Polyesters.

- Poly(glycolic acid)
- Poly(lactic acid)
- Poly(caprolactone)
- Poly(orho esters)

8. Poly(ethylene oxide).

9. Poly(urethanes).

10. Poly(phosphazines).

11. Poly(acrylates).

A biodegradable polymer's chemical structure is given in Fig. 6. The biocomposites components can consist of biofibres and biopolymers.

5 Biocomposites

The biocomposites consist of two biodegradable components; biofibres and biopolymer as illustrated in Fig. 7.

Several combinations of fibres and polymers can be used for the manufacturing of the biocomposites as illustrated in Fig. 8. The choice of its components differsaccording to the composite end-use.

Fiber type, fiber volume fraction, water content, and matrix specifications determine the composite properties. The strength and modulus increase after a certain fiber volume fraction valueminimum,about 30% [3, 67–70]. Figure 8 shows some combinations of the biocomposites components.

Application of cellulose nanofibers increasesconsiderably on the account oftheirmechanical and degradability parameters [71].

6 Polymer Properties

The designer should be acquainted with the followingpolymer properties to assist in the selection of the suitable matrix for a certain application:

1. Intrinsic viscosity measurement
2. Density measurement

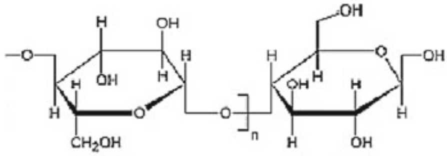
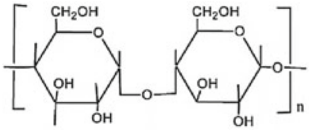
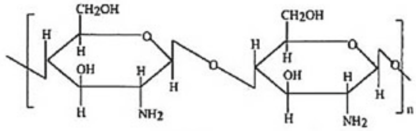
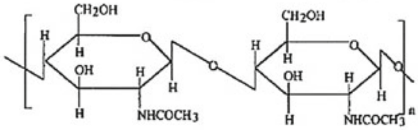
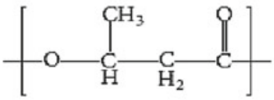
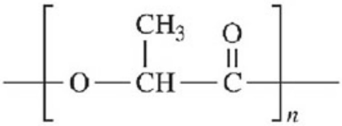
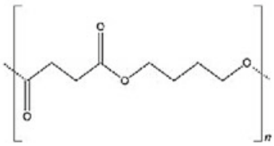
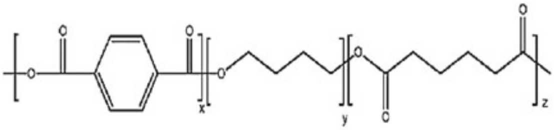
Polymer	Chemical structure
Cellulose	
Amylose	
Chitosan	
Chitin	
Polyhydroxybutyrate (PHB)	
Polylactic acid (PLA)	
Polybutylene succinate (PBS)	

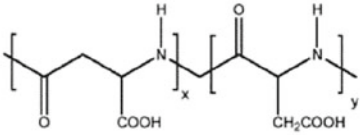
Fig. 6 Chemical structure of some biodegradable polymers [3]

3. Chemical family
4. Tensile properties
5. Flexural strength
6. Thermal—mechanical strength
7. Compression
8. Creep properties
9. Polymer physical properties

Aliphatic aromatic resin (HCR)



Thermal polyaspartate (TPA)



Carboxymethyl cellulose CMC

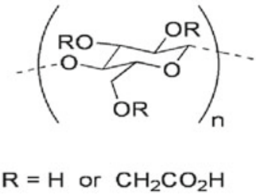


Fig. 6 (continued)

10. Identification of polymer additives
11. Adhesive properties
12. Aging testing for plastics and polymers
13. Chemical resistance testing
14. Environmental testing
15. Ballistic properties
16. Chromatography analysis of polymers
17. Mechanical properties of polymers
18. Mold shrinkage determination

6.1 Polymer Testing Methods

The polymers with different properties, such as the length of the polymer chain and chain structure, are used to form the matrix. There are thermoset and thermoplastic polymers [1]. When the thermoplastic polymer is heated, the de-bonding between chains occurs and the viscosity of the polymer increases, on the contrary to thermoset polymers—on heating of the polymer no movement between the molecules. The International standards used for polymer tests are given in Table 4.

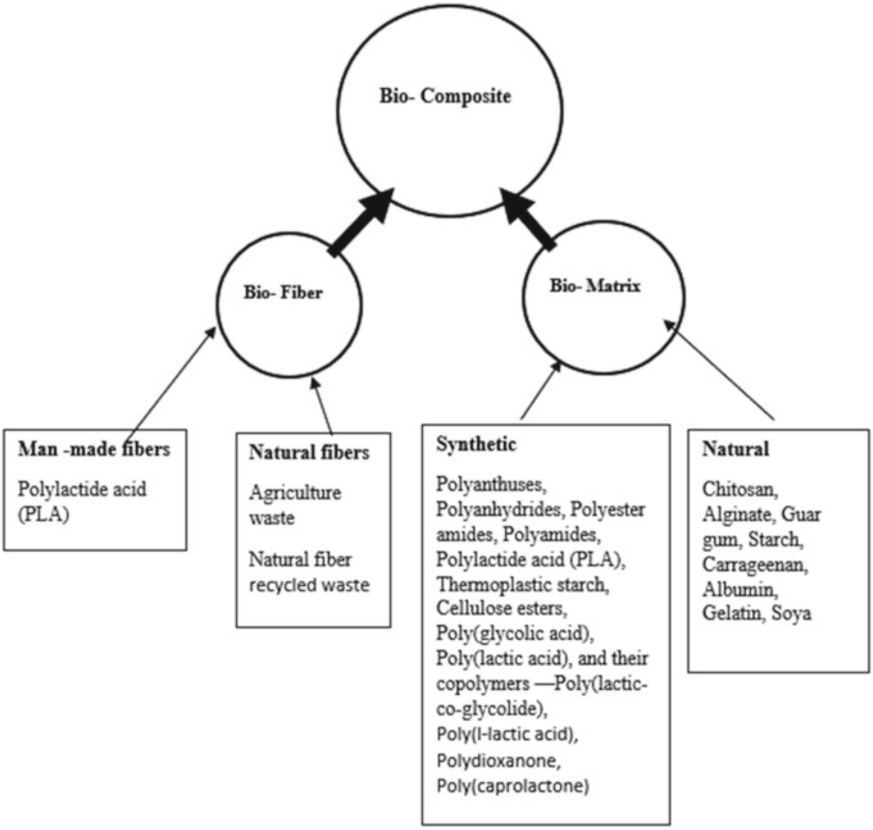


Fig. 7 Components of biocomposites

7 Biodegradation

Biodegradation is the ability of materials to break down to get disintegrated under the effect of the action of microorganisms, bacteria, fungi, enzymes, therefore thedeterioration of material structure [72, 73]. Choice of the type of fibre for biocomposites will mainly depend on its properties, suitability for end-use, and cost. The ideal life cycle of the biodegradable composite may be as given in Fig. 9.

As biodegradable materials, they must completely decompose within a short time after disposal—typically a year or less. Biodegradability of some materials is given in Table 5, which indicates that the biodegradable time of material depends on the surrounding media, and it may vary between few weeks to several years.

In some cases, such as in the case of nylon fabric, it needs 30–40 years for biodegradation time. Biodegradability processes pass through two phases [76].

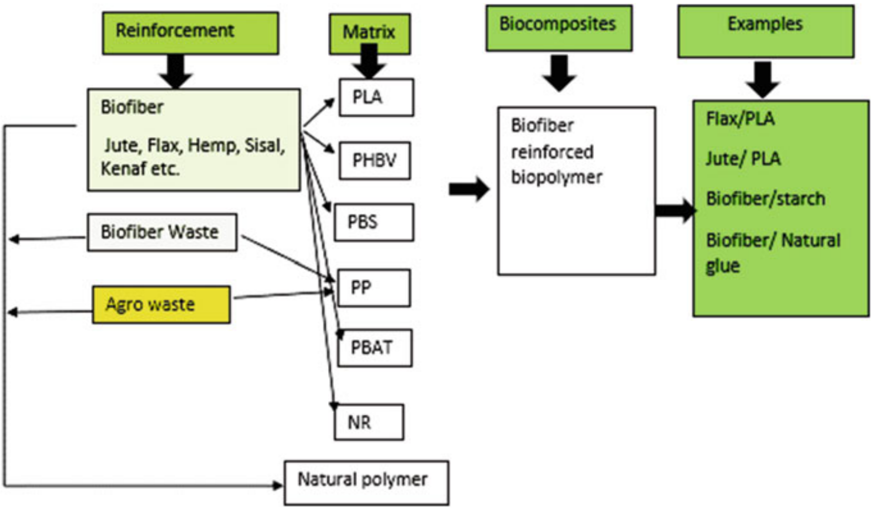


Fig. 8 Types of biocomposites

Table 4 Polymer testing methods

Test	ASTM number	Test	ASTM number
Intrinsic viscosity measurement	D4603	Creep	D7337
Density measurement	D792	Glass transition temperature (TG)	D7028
Tensile properties	D3039 D5083 D638 D638	Thermal expansion properties	D696
Chemical family	E1252 E168,	Deflection temperature under load	D648–01
Flexural strength	D7264	Moisture absorption	D5229
Thermal properties		Chemical resistance	
Compression	D6641 D3410 D695	Flammability	E2058–13a

1. Polymer undergoes significant weight loss, reduction in molecular weight, and fragmentation of soluble low molecular weight compounds.
2. Low molecular weight compounds degraded into CO2, water, and cell biomass (in aerobic conditions), and CH4, CO2, and cell biomass (in anaerobic conditions).

Biodegradability testing may be either aerobic (with oxygen available) or anaerobic (no oxygen available). The following equations indicate these two processes,

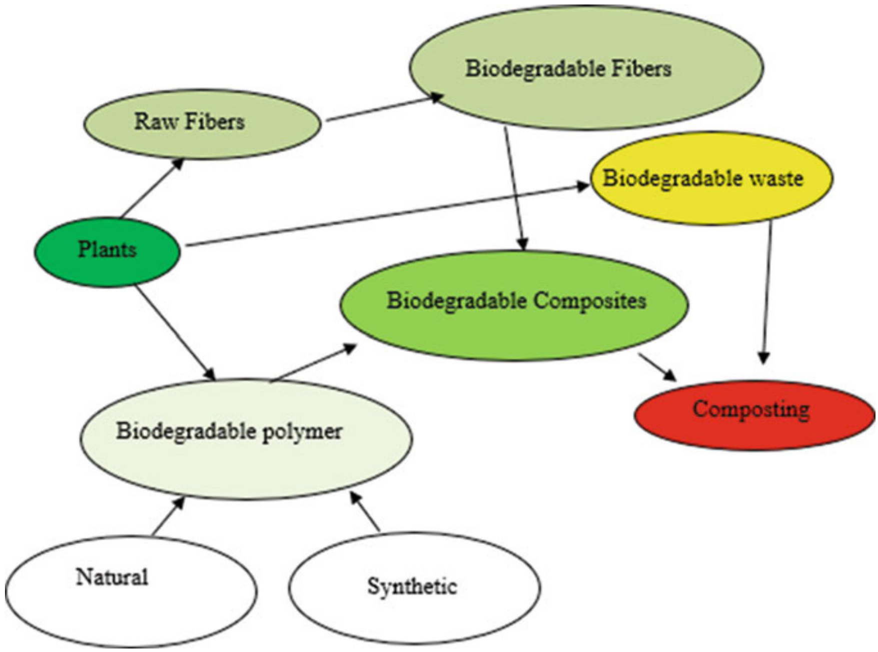


Fig. 9 Ideal life cycle of compostable, biodegradable composite

Table 5 Biodegradability of some materials [74, 75]

Material	Time (Terrestrial environment)	Material	Time (Marin environment)
Paper	Two to five months	Paper towel	Two to four weeks
Cotton T-shirt	Six months	Newspaper	Six weeks
Wool socks	One to five years	Cotton gloves	One to five months
Nylon fabric	Thirty to forty years	Wool gloves	One year
Plastic bags		Plywood	One to three years

where $C_{polymer}$ represents either a polymer or a fragment that is considered to be composed only of carbon, hydrogen, and oxygen [77].

- *Aerobic biodegradation.*
  $C_{polymer} + O_2CO_2 + H_2O + C_{residue} + C_{biomass} + \text{Salts}.$
- *Anaerobic biodegradation.*
  $C_{polymer}\ CO_2 + CH_4 + H_2O + C_{residue} + C_{biomass} + \text{Salts}.$

The biodegradation process is accomplished when the polymer is completely transformed into gaseous products and salts.

Table 6 Bacteria and enzymatic for degradation of polymers [81]

Bacteria	Enzymes	Polymer
Pseudomonas sp. E4	Alkane hydroxylase	LMWPE (Polyethylene)
P. putida AJ	Alkane hydroxylase	Vinyl Chloride (Polystyrene)
P. chlororaphis	Polyurethanase	Polyester, Poly urethane (PUR)
P. aeruginosa	Esterase	Polyester, Poly urethane (PUR)
P. protegens	BC2 12 Lipase	Polyester, Poly urethane (PUR)
P. fluorescen	Protease	Polyester, Poly urethane (PUR)
Pseudomonas sp.	Lipase	Polyethylene terephthalate PET
Pseudomonas sp. AKS2	Esterase	Polyethylene succinate PES
P. stutzeri	PEG dehydrogenase	Polyethylene glycol (PEG)
P. vesicularis PD	Esterase	Polyvinyl alcohol (PVA)
R. arrizus	Lipase	Polyethylene adipate (PEA), Poly butylenes succinate (PBS), and Polycaprolactone (PCL)
P. stutzeri	Serine	hydrolase Polyhydroxy alkanoate (PHA)
Tremetesversicolor	Laccase	Nylon, polyethylene (PE)
Rhodococcusequi	Aryl acylamidase	Polyethylene (PE), Polyurethane (PUR)

It was revealed that the biodegradability of the material depends on the microbial effect and is influenced by the availability of oxygen, temperature, and the availability of water in the surrounding environment. The aerobic degradation in the presence of air will convert into CO2 water and biomass. While in the absence of air it will be converted into CH4, CO2, traces of H2and H2S, and cell biomass [78, 79]. The degradation of the polymer differs according to its chemical structure. The CO2 production is accelerating at the beginning of the test till it reaches a plateau level as shown in Fig. 9. The time taken to reach the fixedvalueof CO2 development in the test was about 75–90 days [80]. Polymer with a high melting point is not expected to disintegrate. Factors, affecting microbial degradation, are moisture, potential hydrogen pH value, temperature [81, 82]. Table 6 gives the types of bacteria and enzymes used in the degradation of the different polymers [81].

8 Natural Fibre Biodegradations

The biodegradation of a material takes place in three steps: degradation, change in the properties of the material, digest of the material.The degradation rate of cellulose material not only depends on the presence of microorganisms and the availability of oxygen [76] but also the physical properties of natural fibres that, in its turn, are mainly determined by the chemical and physical composition. Growth of microorganisms is used in decomposition of substrate depends on several factors [83],and the

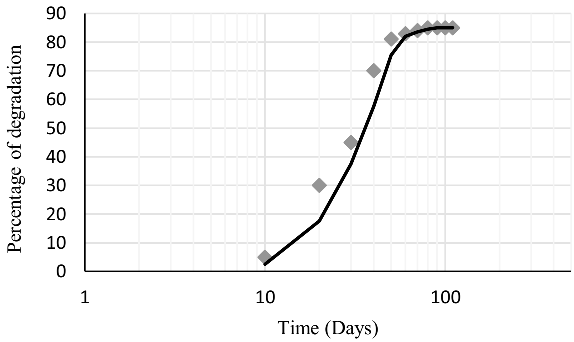


Fig. 10 Percentage of degradation versus time

addition the enzymes results in damaging the structure of the fibres. Biodegradation percentage is evaluated using the following expression:

$$= (\text{mg of } CO_2\text{produced/mg of } CO_2 \text{ theoretical}) \times 100$$

Figure 10 shows the percentage of degradation as a function of time. The loss in weight of the sample starts at a high rate and slows down till it reaches a platform after 100 days.

In the case of the natural fibre (cotton, flax, jute, ramie) or regenerated fibres (viscose rayon, cellulose acetate), the fibre degradability depends on its internal structure, the degree of crystallinity, the cellulose percentage, and the fibre internal structure. The high crystallinity is the degradation rate [84]. Figure 11 shows the percentage of degradation of some fibres after 40 days [72].

Soil test, according to the ISO 11721- 1:2001 and ISO 11721:2003 standard] [85] for biodegradation of cellulosic fabric requires three months.It was revealed that jute and flax are more biodegraded than cotton. The weight loss of the sample after a degradation time of 3 months is shown in Table 7.

It was found that the degradation of the fibres starts at the surface and proceeds inside the fibre structure. The highly crystalline fibre structure will slow down its degradation [86].

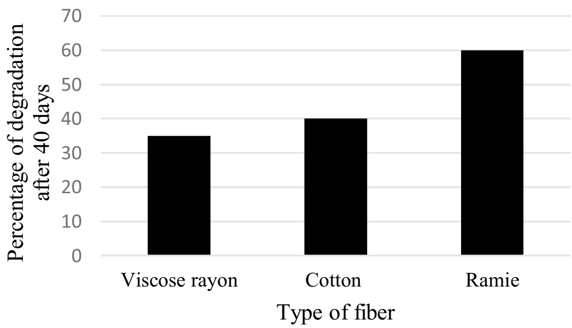


Fig. 11 Percentage degradation of fibres after 40 days [72]

Table 7 Weight loss of fibres after degradation time three months

Fibre type	Weight loss [%]	
	Hydrophilic	Hydrophobic
Cotton	38.69	40.97
Flax	30.27	28.08
Jute	38.79	41.94
Wool	33.16	14.92

9 Degradation of Biocomposites

The composite biodegradation depends on both fibre and polymer biodegradation. With the addition of natural fibre to the biodegradable polymer, the polymer properties and biodegradability of the resulting composites can be changed in comparison to the base polymer [76]. Crystalline structures of the polymer are responsible for the slow degradation of polymers. For example, use polypropylene as a matrix, the composite percent of degradation reaches 5% of that of natural fibre [80].From the experimental results of biodegradability, when using Polylactic acid (PLA) as a matrix for flax and rice husk, the addition of natural fibres slightly improves the biodegradability of Polylactic acid. Again, the use of Kenaf/Polylactic acid composite has a more significant effect on the biodegradation rate than in the case of rice husk/Polylactic acid composite [87]. Polymer biodegradability, standardized testing procedures may be carried out according to (ISO)or (ASTM) standards [88, 89].

Biodegradable composites offer great potential for achieving green, high-performance composites. However, PLA is degraded at a slow rate, ultimately staying at 33% at the end of the 100-day degradation [90, 91].

10 Methods for Determination of Biodegradation

The biocomposites have undergone remarkable improvements to be used for high-performance applications [76].Different standard methods have been applied to evaluate biodegradability as given in Table 8.

Test products are assessed for key chemical properties relating to the material's carbon content and then added to the method test chambers for analysis. Standards are measuring carbon dioxide (CO2) emissions or oxygen consumption under environmentally controlled conditions [92–95]. Biodegradation Testing for Compostable Solids includes ASTM D6400, ISO 16929, and ISO 14855. ASTM D6400 is most often used for composite and also as recommended composability method. The ISO standard organization has several other standards such as ISO 14855 and ISO 17556:2003.

Table 8 Standards for biodegradation determination

Standard No	Test duration	Standard No	Test duration
ASTM D5338	up to 180 days	ISO 9439	28 days
ASTM D5864	28 days	ISO 14593	28 days
ASTM D5988	6 months	ISO 14851	
ASTM D6400		ISO 14852	
BS 8472		ISO 14855	180 days
		ISO 17556:2003	28 days

11 Testing Methods for Natural Fibre/polymer Biocomposites Materials

11.1 Composite Materials Testing Methods

Generally, the mechanical testing of composite material includes:

1. Tensile strength
2. Compression
3. Flexure/bend strength
4. Puncture strength
5. Tear resistance
6. Peel strength
7. Shear strength
8. Delamination strength
9. Bond strength
10. Adhesion strength
11. Creep and stress relaxation
12. Crush resistance
13. Impact strength

12 Torsion

Depending on the application of the polymer and the composite end-use, the test should be chosen. Table 9 gives some basic tests and testing methods for characterization of composite properties that depend on the end-use to provide the required knowledge for a designer of a composite material.

Table 9 Composite testing

Test	ASTM	Test	ASTM
Moisture absorption	D570	Compressibility	D3410
Impact	D7136 / D7136M D3763 D 5628 D256 D1822	Density measurement	D1505-68, D 792
Fibre push-out test	STP1080	Compression	D 6641/ D 6641 M-01 D 695–96 D7137 D 3410
Fibre pull-out	D7332/D7332M	Shear	D5379 D7078 D3518 D3846 D5379
Three points flexural	D790	Fire calorimetry	E 1354
Tensile testing	D882 D5083 D3039 / D3039M	Flammability	D635
Adhesive strength	D 5379 D 5656		

13 Examples of Biofibre Composites Applications

Biocomposites have several new applications. Table 10 gives some examples of the biocomposites application.

In the straw fibre biocomposites different matrices can be used for example, with wheat straw it can be Wheat Gluten, Poly(3-Hydroxybutyrate-Co-Valerate), Natural Rubber, Polypropylene; for Wheat husks, Poly(Lactic Acid);for Rice husk, Poly(3hydroxybutyrate) and Poly(Lactic Acid);for Cornstalk, Natural Rubber, Poly(Lactic Acid); and for Corn husks, Polyethylene, Polypropylene [106–114].

13.1 Processing Methods of Biocomposites

The following is a list of technologies or approaches having implications for the increased use of natural fibres, Table 11. Film stacking, injection molding, and compression molding are the most widely used manufacturing methods.

Several factors affect biocomposites performance, such as processing method, fibre properties, fibre laying, fibre moisture, natural fibre assembly form (loose fibre,

Table 10 Examples of biofibre/polymer composites applications

Material	Composite	Applications	References
Wood raw wastes (WPC)	Wood/plastic and particle size of wood sawdust	Possibility of using waste raw materials for WPC products, like decking and railing systems,	[96]
Wood/natural fibre	Wood/natural fibre-plastic composites (WPCs)	Have great opportunities in residential and industrial sectors, oriented strand board, angles and lam-innated veneer lumber, wood I-joist, decking, railings, and window/door lineals, siding, roofing, and industrial decking	[97]
Straw fibre	Biocomposites with agricultural wastes	Bio-composite boards wheat straw fibres	[98–104]
Husk fibres	Husk fibre/ polymer Biocomposites	Sound absorber	[102, 103]

Table 11 Examples of Natural fibre/Polymer biocomposites and methods of manufacturing [3, 115, 116]

Reinforcement	Manufacturing Technology	Reinforcement	Manufacturing Technology
Non-woven fabrics	Molding under hydraulic pressing	Natural granulated fibres	Melting and composting in the twin-screw extruder
Natural fibres, non-woven	Extrusion molding, compression molding	Agriculture waste	Extrusion (single-screw) and compression molding
Fibers and bagasse blend	Fibre de-fibreized format formation	Fibres (jute, sisal, ramie) fabrics, or hybrids	Pultrusion
Fibres in roving or yarn forms	Extrusions with feeders of yarns	Natural fibres bundles, non-woven mats, bagasse	Concrete manufacturing technology
Non-woven	Resin transfer molding	Rice, sisal, jute, sugarcane bagasse, ramie residues	Sinterization at high temperatures

Table 12 Chemical structure of biodegradable polymers [3]

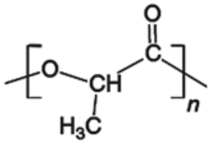
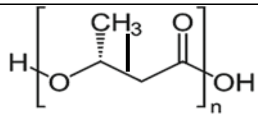
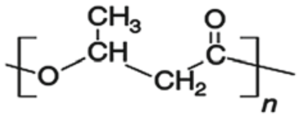
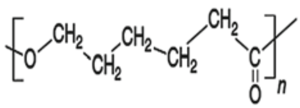
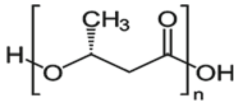
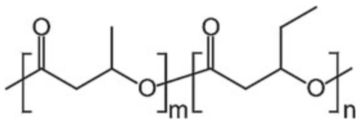
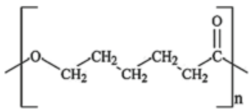
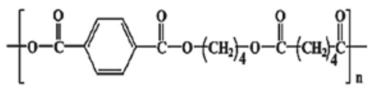
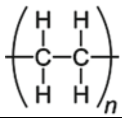
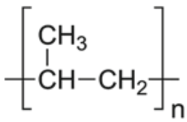
Polymer	Chemical structure
PLA: Poly(lactic acid)	
PHB: Polyhydroxybutyrate	
PHB: Poly(3-hydroxy butyrate) or	
PCL: Poly(ε-caprolactone)	
PHAs: Polyhydroxyalkanoates	
PHBV: Poly(hydroxybutyrate-co-hydroxyvalerate)	
PCL: Polycaprolactone	
PBAT: Poly(butylene adipate-co-terephthalate),	
PE: Polyethylene	
PP: Polypropylene	

Table 13 Examples of biocomposites constitutes [3, 10, 11, 24, 101, 109, 117–124]

Polymer	
Polypropylene **PP**	Flax, Coconut Husks, Hemp, Jute, Palm, Sisal, Sugarcane Bagasse, Wheat Straw
Poly(lactic acid) (**PLA**), Polycaprolactone (PCL) and Copolymers of PLA-PGA (PLGA)	Sugarcane Bagasse
Starch	Agricultural waste, Pseudo Stem
Soy protein	Sisal
Poly(lactic acid)	Flax, Hemp, Jute

yarns, woven, nonwoven, knitted fabric), composite structure (single laminate, multi-laminate), porosity, type of polymer and its properties. In the present time, biopolymers have been found an expanding application in the processing of biocomposites. The chemical structure of the biodegradable polymers is given in Table 12.

In the literature, several applications using biodegradable fibres or waste using different types of biopolymers were intensively investigated [3, 11]. Table 13 gives some application of biocomposites constitutes.

A new trend has arisen where two or more polymers are being selected as matrices for composite applications to get better results over individual biopolymers ones, such as PBAT/PBS blends [125].

References

1. Scarlat N et al (2015) The role of biomass and bioenergy in a future bioeconomy. Policies and facts, Environmental Development 15:3–34
2. Parisi C, Ronzon T (2016) (Online), A global view of bio-based industries: benchmarking and monitoring their economic importance and future developments. EUR 28376 EN; 2016; doi:https://doi.org/10.2788/153649, (Accessed May 5, 2021)
3. El Messiry M (2016) Natural fibre textile composite engineering. A&P Press Inc., USA
4. ChandramohanD., Marimuthu K. (2011), A Review on Natural Fibres. IJRRAS 8(2) :194-206, www.arpapress.com/Volumes/Vol8Issue2/IJRRAS_8_2_09.pdf
5. Dhal P, Mishra S (2013) Processing and properties of natural fibre-reinforced polymer composite. J Mater 2013:1–6. https://doi.org/10.1155/2013/297213
6. Faruk O, Bledzki K, Fink H, Sain M (2012) Biocomposites reinforced with natural fibres. Prog Polym Sci 37(11):1552–1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003
7. Kapatel P (2019) Investigation of Green Composite: Preparation and Characterization of Alkali-Treated Jute Fabric-reinforced Polymer Matrix Composites. Journal of Natural Fibres 18(4):510–519. https://doi.org/10.1080/15440478.2019.1636738
8. Leao A, et al. (2012) Food Agricultural Commodities Team, Unlocking the Commercial Potential of Natural Fibres, publications of FOA
9. Dammer L, Carus M, Raschka A, Scholz L (2013) Market Developments of and Opportunities for bio based products and chemicals, Final Report, nova-Institute for Ecology and Innovation, reference number 52202: 1–67. https://www.eumonitor.nl/9353000/1/j4nvgs5kjg27kof_j9vvik7m1c3gyxp/vjken6y2ivvo/f=/blg338557.pdf
10. Alimuzzaman S, Gong R (2013) Akonda M (2013) Impact Property of PLA/Flax Nonwoven Biocomposite. Conference Papers in Materials Science 136861:1–6

11. Pereira P, Rosa M et al (2015) Vegetal fibres in polymeric composites: a review. Polímeros 25(1):9–22
12. Ticoalu A, Aravinthan T, Cardona F (2010) A review of current development in natural fibre composites for structural and infrastructure applications. Southern Region Engineering Conference 11–12 November 2010, Toowoomba, Australia
13. Balasubramanian J et al (2015) Experimental Investigation of Natural Fibre Reinforced Concrete in Construction Industry. International Research Journal of Engineering and Technology (IRJET) 02(01):179–182
14. Yan L, Chouw N (2015) Sustainable Concrete and Structures with Natural Fibre Reinforcements, eBook, OMICS group. http://www.esciencecentral.org/ebooks/infrastructure-corrosion-durability/sustainable-concrete-and-structures-with-natural-fibre-reinforcements.php.
15. Chowdhury S, Roy S (2013) Prospects of Low Cost Housing in India. Geomaterials 3(2):60–65
16. Wolfe R, Gjinolli A (1996) Cement-Bonded Wood Composites as an Engineering Material, The Use of Recycled Wood and Paper in Building Applications. Conference 1996,Madison, Wisconsin, September 1996, USA http://www.fpl.fs.fed.us/documnts/pdf1997/wolfe97a.pdf
17. Yashas G, Sanjay M, Subrahmanya B, Madhu P et al (2018) Polymer matrix-natural fibre composites: An overview. Cogent Engineering 5(1446667):1–33. https://doi.org/10.1080/23311916.2018.1446667
18. Natural Fibre Composites (NFC) (Online), Market Size, Share & Trends Analysis Report By Raw Material, By Matrix, By Technology, By Application, And Segment Forecasts: 2018 – 2024. https://www.grandviewresearch.com/industry-analysis/natural-fibre-composites-market (accessed May 6, 2021)
19. Dunne R, Desai D, Sadiku R, Jayaramudu J (2016) A review of natural fibres, their sustainability and automotive applications. Journal of Reinforced Plastics 35(13):1041–1050
20. Sen T, Reddy H (2011) Various industrial applications of hemp, kenaf, flax and ramie natural fibres. Int J InnovatManagTech 2:192–198
21. Desai J, Pandey N (1971) Microbial Degradation of Cellulose Textiles. J Sci Ind Res 30:598–606
22. Bisanda N (2000) The effect of alkali treatment on the adhesion characteristics of sisal fibres. Appl Compos Mater 7(5–6):331–339. https://doi.org/10.1023/A:102658602
23. Huda S, Drzal T, Ray D, Mohanty K, Mishra M (2008) Natural-fibre composites in the automotive sector. In Properties and performance of natural-fibre composites, Ed. Pickering K L: 221–268. Woodhead: Elsevier
24. Graupner N, Herrmann A, Müssig J (2009) Natural and man-made cellulose fibre-reinforced poly (lactic acid)(PLA) composites: an overview about mechanical characteristics and application areas, Composites Part A. Applied Science and Manufacturing 40(6–7):810–821
25. El Messiry M, El Deeb R (2016) Analysis of the Wheat Straw/Flax Fibre Reinforced Polymer Hybrid Composites. J Appl Mech Eng 5:240. https://doi.org/10.4172/2168-9873.1000240
26. Yasina M, Bhuttob A, Karimb A (2010) Efficient utilization of rice-wheat straw to produce value added composite products. Int J Chemical and Environmental Engineering 1:136–148
27. Mantanis E, Nakosb P, Berns J, Rigal L (2000) Urning Agricultural Straw Residues Into Value –Added Composite Products: A New Environmentally Friendly Technology, Conference: Proc. of the 5th International Conference on Environmental Pollution, Aug. 28–31, 2000, Aristotelian University, Thessaloniki, Greece
28. Popp J, Kov´acs S, Ol´ah J, Div´eki Z, Bal´azs E, (2021) Bioeconomy: Biomass and biomass-based energy supply and demand. New Biotechnol 60:76–84
29. Dungani R, Karina M, Subyakto M, Sulaeman A, Hermawan D, Hadiyane A (2016) Agricultural waste fibres towards sustainability and advanced utilization: A review. Asian J. Plant Sci. 15:42–55
30. Islam S, El Messiry M, Sikdar P, Seylar J, Bhat G (2020) Microstructure and performance characteristics of acoustic insulation materials from postconsumer recycled denim fabrics. Ind text J:1–27 https://doi.org/10.1177/1528083720940746
31. Muthu S (2017) Textiles and clothing sustainability: recycled and upcycled textiles and fashion. Springer, Singapore

32. EPA (2020), (Online), Facts and Fig.s about materials, waste and recycling, www.epa.gov/facts-and-Fig.s-about-materials-waste-and-recycling/textiles-material-specific-data (accessed 26 April, 2020)
33. Wang Y (2010)Fibre and textile waste utilization. Waste Biomass Valor 1: 135–143
34. Aladejana J, Wu Z, Fan M, Xie Y (2020) Key advances in development of straw fibre biocomposite boards: An overview. Mater. Res. Express 7(1):1–19
35. Piotrowski S, Mand C, Essel R (2015) Global Bioeconomy in the conflict between biomass supply and demand. Ind Biotechnol 11:1–13
36. Composite world, (online) Natural fibre composites: What's holding them back? https://www.compositesworld.com/articles/natural-fibre-composites-whats-holding-them-back (accessed May 3, 2021)
37. Michalina F, Katarzya J, George W (2010) Handbook of Biodegradation, Biodeterioration and Biostabilization. ChemTec Publishing, Toronto
38. Bamboo garden. [Online] http://www.bamboogarden.com/care.htm (accessed May 6, 2016)
39. FAONewsroom.[Online] http://www.fao.org/NEWSROOM/EN/news/2006/1000285/index.html (accessed May 6, 2016)
40. Natural fibres. [Online] http://www.fao.org/docrep/007/ad416e/ad416e06.htm (accessed May 6, 2016)
41. Crop Science. [Online] http://www.bayercropscience.cl/soluciones/fichacultivo.asp?id=129 (accessed May 6, 2016)
42. Hemp. [Online] https://en.wikipedia.org/wiki/Hemp (accessed May 6, 2016).
43. Agave. [Online] https://en.wikipedia.org/wiki/Agave_fourcroydes(accessed May 6, 2016)
44. Abaca. [Online] https://en.wikipedia.org/wiki/Abac%C3%A1 (accessed May 6, 2016)
45. Yucca faxoniana. [Online] https://commons.wikimedia.org/wiki/File:Yucca_faxoniana_2.jpg (accessed May 6, 2016)
46. Jute. [Online] http://www.bangla-bagan.com/2015/08/13/growing-a-jute-plant-in-the-uk/(accessed May 6, 2016)
47. Ceiba pentandra. [Online] https://en.wikipedia.org/wiki/Ceiba_pentandra (accessed May 6, 2016)
48. Hibiscus cannabinus. [Online] https://en.wikipedia.org/wiki/Kenaf (accessed May 6, 2016)
49. Cannabis sativa. [Online] https://commons.wikimedia.org/wiki/File:U.S._Government_Medical_Marijuana_crop._University_of_Mississippi._Oxford.jpg#/media/File:U.S._Government_Medical_Marijuana_crop._University_of_Mississippi._Oxford.jpg(accessed May 6, 2016)
50. Urticadioica. [Online] https://upload.wikimedia.org/wikipedia/commons/a/aa/Stinging_nettle_plants.JPG(accessed May 6, 2016)
51. Elaeisguineensis. [Online] https://en.wikipedia.org/wiki/Palm_oil (accessed May 6, 2016)
52. Attalea (palm). [Online] https://commons.wikimedia.org/wiki/File:Attalea_funifera_Mart._ex_Spreng._(6709151365).jpg (accessed May 6, 2016)
53. Pineapple. [Online] https://commons.wikimedia.org/wiki/Category:Pineapple_fields_in_the_United_States#/media/File:Starr_020630-0021_Ananas_comosus.jpg(accessed May 6, 2016)
54. Phormium Amazing Red. [Online] https://commons.wikimedia.org/wiki/File:Phormium_Amazing_Red_1.jpg#/media/File:Phormium_Amazing_Red_1.jpg (accessed May 6, 2016)
55. Layth M, Ansari M, Pua G, Jawaid M, Islam M (2015) A Review on Natural Fibre Reinforced Polymer Composite and Its Applications. International Journal of Polymer Science 2015. Article ID 243947:1–15. https://doi.org/10.1155/2015/243947
56. Van der Zee M, Stoutjesdijk H, Van der Heijden W, De Wit D (1995) Structure-biodegradation relationships of polymeric materials & Effect of degree of oxidation of carbohydrate polymers. Journal of Polymers and the Environment [e-journal] 3(4):235–242, Available through: SpringerLink (Accessed 25 January 2021)
57. Abba A, Nur Z, Salit M (2013) Review of agro waste plastic composites production. J. Miner. Mater. Charact. Eng. 1:271–279

58. Cicala G, Cristaldi G, Recca G, et al. (2010) Composites based on natural fibre fabrics. In: Woven fabric engineering, InTech.https://www.intechopen.com/books/woven-fabric-engineering/composites-based-on-natural-fibre-fabrics
59. Gupta M (2016) Srivastava R (2016) Mechanical Properties of Hybrid Fibres-Reinforced Polymer Composite: A Review. Polym-Plast Technol Eng 55(6):626–642. https://doi.org/10.1080/03602559.2015.1098694
60. Pao C, Yeng C (2019) Properties and characterization of wood plastic composites made from agro-waste materials and post-used expanded polyester foam. Journal of Thermoplastic Composite 32(7):951–966
61. Polymer Structure (2021), (online), Iowa State University Center for nondestructive Evaluation NDE-Ed.Org. https://www.nde-ed.org/Physics/Materials/Physical_Chemical/PhaseTransformationTemp.xhtml
62. (accessed May 3, 2021)
63. Ghanbarzadeh B, Almasi H (2013) Biodegradable Polymers, Biodegradation - Life of Science, chapter 6, Ed. Chamy R, Pub. InTech. [Online] 2013. (Accessed March 29, 2021)
64. Luckachan G, Pillai C (2011) Biodegradable Polymers- A Review on Recent Trends and Emerging Perspectives. J PolymEnviron 19:637–676. https://doi.org/10.1007/s10924-011-0317-1
65. Netravali A (2005) Chapter 9. Biodegradable natural fibrecomposites .Biodegradable and sustainable fibres. Edited by R. S. Blackburn. Published by Woodhead Publishing Limited in association with The Textile Institute Abington Hall, Abington, Cambridge CB1 6AH, 2005, England
66. Masuelli M (2013) Introduction of fibre-reinforced polymers − polymers and composites: concepts, properties and processes, fibre reinforced polymers - the technology applied for concrete repair. Ed. Masuelli, M.A., Pub. InTech, 2013
67. Bos H, M¨ussig J, Jvan den Oever J, (2006) Mechanical properties of short-flax-fibre reinforced compounds. Compos A 37(10):1591–1604
68. Bos H (2004) The potential of flax fibers as reinforcement for composite materials. Ph.D. Thesis, TechnischeUniversiteitEindhoven, Eindhoven, The Netherlands
69. Garkhail S, Heijenrath R, Peijs T (2000) Mechanical properties of natural-fibre-mat-reinforced thermoplastics based on flax fibres and polypropylene. Appl Compos Mater 7(5–6):351–372
70. NishinoT, (2004) Natural fiber sources, in Green Composites: Polymer Composites and the Environment. CRC Press, BocaRaton, Fla, USA
71. Espert A, Vilaplana F, Karlsson S (2004) Comparison of water absorption in natural cellulosic fibres from wood and one-year crops in polypropylene composites and its influence on their mechanical properties. Compos A 35(11):1267–1276
72. Kalia S et al (2011) Cellulose-Based Bio- and Nanocomposites: A Review. International Journal of Polymer Science 2011:1–35
73. Marielis C et al (2020) Effect of chemical and morphological structure on biodegradability of fibre, fabric, and other polymeric materials. BioResources 15(4):9786–9833
74. Albertsson A, Karlsson S (1994) Chemistry and technology of biodegradable polymers. Blackie, Glasgow, pp 7–17
75. Science learning hub (2018), (online) Measuring biodegradability, Science Learning Hub. Retrieved 2018–09–19 (Accessed March 29, 2021)
76. Vert M, Hellwich D (1993) (online) Marine Debris Timeline Biodegradation, C-MORE, citing Mote Marine Laboratory, (Accessed March 29, 2021)
77. Muniyasamy S et al (2013) Biodegradability and Composability of Lignocellulosic. J. Renew. Mater. 1(4):253–272
78. Van der Zee M (2011) Analytical Methods for Monitoring Biodegradation Processes of Environmentally Degradable Polymers, Handbook of Biodegradable Polymers: Synthesis, Characterization and Applications, First Edition. Edited by Andreas Lendlein, Adam Sisson,© 2011 Wiley-VCH Verlag GmbH & Co. KGaA. Published 2011 by Wiley-VCH Verlag GmbH & Co. KGaA

79. Tuomela M et al (2000) Biodegradation of lignin in a compost environment: a review. Biores Technol 72:169–183
80. Sharma M (2021) Biodegradable Polymers: Materials and their Structures. CRC Press, 2021, USA
81. Chattopadhyay S, Singh S, Pramanik N et al (2011) Biodegradability Studies on Natural Fibres Reinforced Polypropylene Composites. J Appl Polym Sci 121:2226–2232
82. Iram D, Riaz R, Iqbal R (2019) Usage of Potential Micro-organisms for Degradation of Plastics. Open J Environ Biol 4(1): 7–15. DOI: http://dx.doi.org/https://doi.org/10.17352/ojeb.000010]
83. Tokiwa Y, Calabia B, Aiba S (2009) Biodegradability of Plastics. Int J Mol Sci 10(9):3722–3742
84. Ferdes M, Dinca M, Moiceanu G, Bianca S, Zabava G (2020) Microorganisms and Enzymes Used in the Biological Pretreatment of the Substrate to Enhance Biogas Production: A Review Sustainability 12:7205. https://doi.org/10.3390/su12177205
85. Pantani R, Sorrentino A (2013) Influence of crystallinity on the biodegradation rate of injection-mouldedpoly(lactic acid) samples in controlled composting conditions. Polym Degrad Stab 98(5):1089–1096
86. Arshad K, Mujahid M (2011) Biodegradation of Textile Materials. Master Thesis for the Master in Textile Technology, School of Engineering University of Boras, Sweden
87. Zambrano, et al (2020) Biodegradability fibre/fabric. BioResources 15(4):9786–9833
88. Yussuf A, Massoumi I, Hassan A (2010) Comparison of Polylactic Acid/Kenaf and Polylactic Acid/Rise Husk Composites: The Influence of the Natural Fibres on the Mechanical, Thermal and Biodegradability Properties. J PolymEnviron 18:422–429
89. ISO 17088:2021.Specification of compostable plastics. https://www.iso.org/obp/ui/#iso:std:iso:17088:ed-3:v1:en
90. ASTM D6400–12 (2012) Standard specification for labeling of plastics designed to be aerobically composted in municipal or industrial facilities. https://standards.globalspec.com/std/13327302/ASTM%20D6400
91. Xie L et al (2014) Toward faster degradation for natural fibre reinforced poly(lactic acid) biocomposites by enhancing the hydrolysis-induced surface erosion. J PolymRes 21:357–357. https://doi.org/10.1007/s10965-014-0357-z
92. Chauhan A, Chauhan P (2013) Natural Fibres and Biopolymer. J Chem Eng Process Technol S6:1–4. https://doi.org/10.4172/2157-7048.S6-001
93. Castellani F, Esposito A, Stanzione V, Altieri R (2016) Measuring the Biodegradability of Plastic Polymers in Olive-Mill Waste Compost with an Experimental Apparatus. Advances in Materials Science and Engineering 2016. Article ID 6909283:1–7
94. International Organization for Standardization (ISO), Specification for compostable plastics, ISO 17088:2012, International Organization for Standardization (ISO), Geneva, Switzerland, 2012
95. European Committee for Standardization (CEN), Packaging— requirements for packaging recoverable through composting and biodegradation—test scheme and evaluation criteria for the final acceptance of packaging," CEN EN 13432:2000, 2000.
96. Emirates Authority for Standardization & Metrology (ESMA). Standard & Specification for Oxo-biodegradation of Plastic bags and other disposable plastic objects. http://www.puntofocal.gob.ar/notific_otros_miembros/are26_t.pdf
97. Križan P, Beniak J, Matúš M, Šooš L, Kolláth L (2017) Research of plastic and wood raw wastes recovery. Adv Mater Lett 8(10):983–986
98. Smith P, Wolcott M (2006) Opportunities for wood/natural fibre plastic composites in residential and industrial applications. Forest Prod. J. 56(3):4–11
99. Preetesh S (2020) A Study on the Utilization of the Biomass to Produce Biodegradable Board. Journal of critical reviews 7(09):3158–3166
100. Panthapulakkal S, Sain M (2015) The use of wheat straw fibres as reinforcements in composites Biofibre Reinforcements in Composite Materials. Ed. Faruk O and Sain M (Woodhead Publishing)

101. Chen R, Salleh M et al (2015) Biocomposites based on rice husk flour and recycled polymer blend: effects of interfacial modification and high fibre loading. BioResources 10:6872–6885
102. Battegazzore D, Bocchini S, Alongi J, Frache A (2014) Rice husk as bio-source of silica: preparation and characterization of PLA–silica bio-composites RSC Adv. 4:54703–54712
103. Hýsek Š, Podlena M, Bartsch H, Wenderdel C, Böhm M (2018) Effect of wheat husk surface pre-treatment on the properties of huskbased composite materials. Ind Crops Prod 125:105–133
104. Cobo P, de Espinosa FM (2013) Proposal of cheap microperforated panel absorbers manufactured by infiltration. Appl Acoust 74:1069–1075
105. Jayamani E, Hamdan S, Rahman M, Bakri M (2015) Study of sound absorption coefficients and characterization of rice straw stem fibres reinforced polypropylene composites. BioResources 10:3378–3392
106. Montaño-Leyva B, da Silva GGD, Gastaldi E, Torres-Chávez P, Gontard N, Angellier-Coussy H (2013) Products, biocomposites from wheat proteins and fibres: structure/mechanical properties relationships. Ind Crops Prod 43:545–555
107. Berthet M, Gontard N, Angellier-Coussy H (2015) Technology, Impact of fibre moisture content on the structure/mechanical properties relationships of PHBV/wheat straw fibresbiocomposites. Compos Sci Technol 117:386–391
108. Masłowski M, Miedzianowska J, Strzelec K (2017) Natural rubber biocomposites containing corn, barley and wheat straw. Polym Test 63:84–91
109. Jagadeesh D, Sudhakara P, Lee D, Kim H, Kim B, Song J (2013) Mechanical properties of corn husk flour/PP bio-composites. Green composites 26:213–217
110. Tran T, Bénézet J, Bergeret A (2014) Rice and Einkorn wheat husks reinforced poly(lactic acid) (PLA) biocomposites: effects of alkaline and silane surface treatments of husks. Ind Crops Prod 58:111–124
111. Sánchez-Safont E, Aldureid A, Lagarón J, Gámez-Pérez J, Cabedo L (2018) Biocomposites of different lignocellulosic wastes for sustainable food packaging applications. Compos B Eng 145:215–225
112. Masłowski M, Miedzianowska J, StrzelecK(2019) Natural Rubber Composites Filled with Crop Residues as an Alternative to Vulcanizates with Common Fillers, Polymers. 11, 972. https://doi.org/10.3390/polym11060972
113. Luo H, Zhang C, Xiong G, Wan Y (2016) Effects of alkali and alkali/silane treatments of corn fibres on mechanical and thermal properties of its composites with polylactic acid. Polym Compos 37:3499–3507
114. Trigui A, Karkri M, Pena L, Boudaya C, Candau Y, Bouffi S, Vilaseca F (2013) Thermal and mechanical properties of maize fibres– high density polyethylene biocomposites. J Compos Mater 47:1387–1397
115. Wang D, Xuan L, Han G, Wong A, Wang Q, Cheng W (2020) Preparation and characterization of foamed wheat straw fibre/polypropylene composites based on modified nano-TiO2 particles. Composites Part A. Applied Science and Manufacturing 128, 105674
116. Brouwer W (2009) Natural fibre composites in structural components: alternative applications for sisal. FAO, Economic and Social Development Department (online) http://www.fao.org/docrep/004/y1873e/y1873e02.htm#TopOfPage (accessed Feb 10, 2015)
117. Bio-base news. (Online) http://news.bio-based.eu/biocomposites/ (accessed June 28, 2015)
118. Mano B, Araújo JR, Spinacé M, De Paoli M (2010) Polyolefin composites with curauafibres: effect of the processing conditions on mechanical properties, morphology and fibres dimensions. Compos Sci Technol 70(1):29–35
119. John M, Anandjiwala R (2009) Chemical modification of flax reinforced polypropylene composites. Composites Part A. Applied Science and Manufacturing 40(4):442–448
120. Yan Z, Wang H, Lau K, Pather S, Zhang JC, Lin G, Ding Y (2013) Reinforcement of polypropylene with hemp fibres. Compos B Eng 46:221–226
121. Acha B, Reboredo M, Marcovich N (2007) Creep and dynamic mechanical behavior of PP–jute composites: effect of the interfacial adhesion. Composites Part A. Applied Science and Manufacturing 38(6), 1507–1516

122. Kaewkuk S, Sutapun W, Jarukumjorn K (2013) Effects of interfacial modification and fibre content on physical properties of sisal fibre/polypropylene composites. Compos B Eng 45(1):544–549
123. Cerqueira E, Baptista C, Mulinari D (2011) Mechanical behaviour of polypropylene reinforced sugarcane bagasse fibres composites. Procedia Engineering 10:2046–2051
124. Guimarães J, Wypych F, Saul C, Ramos L, Satynarayana K (2010) Studies of the processing and characterization of corn starch and its composites with banana and sugarcane fibres from Brazil. Carbohyd Polym 80(1):130–138
125. Kim J T, Netravali A (2010) Mercerization of sisal fibres: effect of tension on mechanical properties of sisal fibre and fibre-reinforced composites. Composites Part A. Applied Science and Manufacturing 41(9):1245–1252
126. Muthuraja R, Misraa M, Mohanty A(2015) Binary blends of poly(butylene adipate-coterephthalate) and poly(butylene succinate): A new matrix for biocomposites applications. AIP Conference Proceedings 1664, 150009; https://doi.org/10.1063/1.4918505

Bio Fibre Composites: Modification and Processing Techniques

Role of Different Forms of Bamboo and Chemical Treatment on the Mechanical Properties of Compression Molded Green Composites

Kishore Debnath and Gorrepotu Surya Rao

Abstract Green composites are sustainable materials that are composed of biodegradable polymer and naturally occurred fibre. These biodegradable green composites are light in weight and possess fairly good mechanical properties. The incorporation of a higher percentage of natural fibre into the polymer, selection of suitable coupling agent and treatment method, to name a few, makes it quite challenging to develop green composites. Also, the mechanical response of these composites is determined by many factors such as fibre-matrix bonding, surface treatment of fibre, fibre weight ratio, addition of various additives, and fibre aspect ratio. It is a dire need to develop green composite with superior mechanical properties to extend their application in various engineering fields. In the present study, bamboo in different forms like strip, short fibre, and woven mat was reinforced with biodegradable polylactic acid (PLA) to develop the green composites. The different forms of bamboo chosen for investigation were also chemically treated. Two types of chemical treatments were performed using sodium hydroxide (NaOH) and potassium hydroxide (KOH) to improve the surface characteristics of the different forms of bamboo. The green composite developed in this study was manufactured by compression molding. The properties of chemically treated and non-treated green composite specimens were experimentally evaluated and compared.

Keywords Green composite · Short fibre · Woven mat · Strip · Chemical treatment · Tensile and flexural properties

1 Introduction

Composite materials are preferred as the most affordable materials because of their multifunctional properties like (a) high strength, (b) high modulus, and (c) low density as compared to the traditional materials. Two or more materials having different properties are mixed together to obtain composite materials. As a result, the characteristic

K. Debnath (✉) · G. S. Rao
Mechanical Engineering, NIT Meghalaya, Shillong, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_6

of the resultant composites is quite different from individual constituents. The utility of the green composites has increased tremendously in recent times due to the nonenvironmental friendly behaviour of the synthetic composites. Green composites are a mixture of biodegradable polymer and natural fibre and thus can be disposed to the environment [1–3].

Polylactic acid (PLA) is a largely produced biodegradable polymers in the world. The striking features of PLA are (a) high strength, (b) high modulus, (c) high stiffness, and (d) less energy is required for processing. PLA is extracted from renewable sources like (a) corn starch, (b) cassava roots, and (c) sugarcane. Because of the transparency, biodegradability, and good mechanical properties, biodegradable polymer PLA is extensively used in various applications like (a) food packaging, (b) medical and healthcare, and (c) structural and textile applications.

Green composites composed of PLA and natural fibre has promising mechanical performance as compared to the composites composed of synthetic fibre and polymer. Rawi et al. [4] evaluated the different properties of compression molded green composites composed of PLA and bamboo fibre. The composite properties were better in warp direction of the fiber than the weft direction. The maximum braking force in the weft and warp and directions were 355 N and 649 N, respectively. Porras and Maranon [5] studied the properties of green composites of PLA reinforced with woven bamboo fabric by compression molding. The composite of transverse bamboo fabric attained better mechanical properties than the longitudinal bamboo fabric composite. The maximum modulus and strength of the composite were 1.75 GPa and 77.58 MPa. The modulus and strength properties of the same composite under flexural loading were 1.2 GPa and 149.34 MPa. It was also stated that the composite properties were better than the neat PLA. Sukmawan et al. [6] fabricated cross-ply green composites using chemically treated bamboo by compression molding. The maximum modulus and strength of cross-ply (0/90) composite were attained as 10.5 GPa and 223 MPa. The strength and modulus properties of composite were enhanced by 7.2 and 4.9 times when compared one-on-one with neat PLA. Wang et al. [7] used compatibilizer to study its effect on the performance of bamboo flour/PLA composites manufactured by means of compression molding. The composite properties were improved because of the addition of PLA-g-glycidyl methacrylate (GMA) compatibilizer when compared with composites without compatibilizer. The properties were improved with an increase in the compatibilizer to 15 phr, after that gradual decrement was noticed. At 15 phr of PLA-g-GMA, the maximum modulus and strength of the composite reached to 6.3 GPa and 60 MPa with an increment of 44% and 135% as compared to non-compatibilized composite. The addition of compatibilizer resulted in even dispersion of bamboo flour. Kang and Kim [8] studied the properties of saline treated bamboo/PLA fabricated by compression molding. By increasing the bamboo fibre content by 10%, 20%, and 30%, the maximum tensile strength achieved was 16.2 MPa, 11.8 MPa, and 15.0 MPa. The tensile strength of different composites showed 50% lower than neat PLA. The surface modification was quite useful to extract lignin which affected the strength of the composite. The flexural properties were also deteriorated as compared to neat

PLA. Lee and Wang [9] used bio-based coupling agent to study its effect on the properties of bamboo/PLA manufactured by compression molding. With an increase in the NCO content to 0.33% to the composite of bamboo/PLA (70/30%), the strength and modulus improved from 29 to 49.2 MPa and 2.66 to 2.94 GPa. Kumar et al. [10] fabricated bamboo/PLA/cloisite 30B hybrid composite to evaluate its properties. The performance of the hybrid composites showed better than the neat PLA and bamboo/PLA. The maximum modulus and strength (tensile) of the hybrid composites were 4.87 GPa and 48.56 MPa. Whereas the maximum modulus and strength under flexural loading were obtained as 7.62 and 78.11 MPa. The fibre-matrix adhesion was improved due to the addition of nanofillers. This resulted in better properties of the hybrid composite. Li et al. [11] analysed the effect of interfacial compatibilization on the performance of bamboo/PLA green composites. Alkaline (NaOH) treated bamboo/PLA performed better in terms of tensile strength (19.43 MPa), modulus (5.1 GPa), and elongation at break (5.59%). These properties were increased by 20.7, 13.3, and 30.1% as compared to nontreated fabric composites. NaOH treatment of bamboo fibre improved the contact area between individual fibres by removing the impurities, hemicellulose, pectin, and waxes. Kobayashi et al. [12] fabricated bamboo (continuous fibre)/PLA composite by compression molding and studied the effect of mold condition on the performance of the composite. Both strength and modulus were increased as the mold temperature increased to 190 °C. Fazita et al. [13] investigated the recycling and biodegradability of compression molded bamboo/PLA composite. The tensile properties of the recycled composite deteriorated whereas the flexural properties were improved when compared with nonrecycled bamboo/PLA composites. The decrement in the tensile properties was due to remolding the matrix in the process of recycling. The shortened and dispersed bamboo fibre was the result of an improvement in the flexural properties. Chen et al. [14] studied and implemented a new method to improve the bonding characteristics between the polymer (PLA) and fibre (bamboo). A substantial improvement in the tensile properties was noticed by the addition of epoxydized soyabean oil (ESO) to the composite. The interface layer of ESO caused an effective load transfer. Dehghan et al. [15] investigated the effect of heat treatment and bamboo mesh size on the performance of bamboo/PLA composites. The modulus of elasticity was increased with the addition of 35% to 55% bamboo due to higher contact area between the fibres. However, the strength was decreased by the addition of 35% to 55% fibre. The decrement was due to the insufficient load transfer and poor fibre-matrix adhesion. Qian et al. [16] varied the fibre content to study its effect on the properties of bamboo/PLA manufactured by compression molding. The addition of bamboo particles created poor surface interaction. Thus, the properties of the composite dropped down when compared with pure PLA. The addition of ultra-fine bamboo fibre resulted in achieving better mechanical properties than the composite of bamboo particles/PLA. Srisuk et al. [17] fabricated the composites composed of bamboo charcoal (BC) as reinforcement and PLA as a matrix by varying the weight ratio of the fibre. The addition of BC to PLA improved the mechanical properties. The addition of more BC to the composite resulted in a decrease in the strength of the BC/PLA composites. Qian et al. [18] examined the effect of alkaline pre-treatment on the performance of bamboo/PLA composite.

NaOH treatment of the bamboo fibre resulted in an improvement in the properties of the composite. The modulus and strength of the nontreated bamboo/PLA were noted as 406.41 MPa and 36.67 MPa. The composite attained the maximum strength and modulus as 44.21 MPa and 668.3 MPa with an improvement of 20.56% and 64.44% as compared to nontreated composite due to the treatment of bamboo for 3 h. Lin et al. [19] investigated the influence of synergetic and alkali treatment on the properties of bamboo/PLA. Compared to the nontreated bamboo/PLA, the flexural and tensile strength of dopamine treated bamboo/PLA was improved by 13.6% and 22.6%, respectively. The addition of dopamine modified the chemical links between the matrix and fibre, as a result, the stress resistivity of the composite was improved. Wang et al. [20] studied the performance of PLA filled with chemically treated bamboo fibre. The elongation and strength of the NaOH treated composites under tensile loading was improved by 49% and 84% whereas a noticeable decrement was observed in the tensile modulus by 21%. Zuo et al. [21] studied the effect of the compatible interface of nano-SiO_2 on the properties of bamboo/PLA composites. The uniform dispersion of nano-SiO_2 particles resulted in improved tensile properties. The energy absorption rate and stress distribution between the matrix and fibre was improved with the nanoparticles content. Rizal et al. [22] studied the degradation behavior and properties of bamboo cellulose nanofibre reinforced with PLA-chitosan matrix-based bio-nanocomposite. The modulus and strength of the PLA/chitosan matrix with 5% bamboo fibre biocomposite exhibited peak values of 89 MPa and 8.5 GPa. Whereas the strength and modulus of neat PLA were 65 MPa and 2.5 MPa. In comparison to pure PLA, the similar bio-composite showed an incremental trend in flexural strength from 70 to 91 MPa. It was also concluded that the addition of bamboo nanofibre improved the compatibility which led to even stress distribution throughout the composite interface. Nurnadia et al. [23] evaluated the properties of bamboo/PLA-based green composite by implementing Taguchi L_9 experimental plan for optimization. The bamboo/PLA composite attained the strength and modulus of 49.33 MPa (tensile strength), 0.79 GPa (tensile modulus), 69.87 MPa (flexural strength), and 2.9 GPa (flexural modulus). These properties of composites were obtained at fibre size of 150–250 μm, fibre loading of 30%, and mold temperature of 190 °C. At this parametric condition, a homogeneous dispersion of bamboo fibre on the PLA interface was noticed. Ochi [24] analysed the influence of mold temperature and bamboo fibre content on the performance of long bamboo fibre/PLA-based green composite that was fabricated by hot-press compression. The maximum flexural modulus and strength of the green composite were 6.83 GPa and 273.28 MPa which were obtained by maintaining the mold temperature as 160 °C and fibre loading as 70%. Quin et al. [25] analysed the effect of maleic anhydride on the performance of bamboo particles/PLA composite fabricated by hot pressing. The NaOH treated bamboo/PLA composite with 1% MAH exhibited improved properties. With an increase in the MAH content to 2.5%, the authors noticed a decrement in the properties due to the high oxidation effect with the compatibilizer. As a result, molecular chain mobility was increased and an observable decrement in the crystallinity was resulted in degrading the mechanical performance.

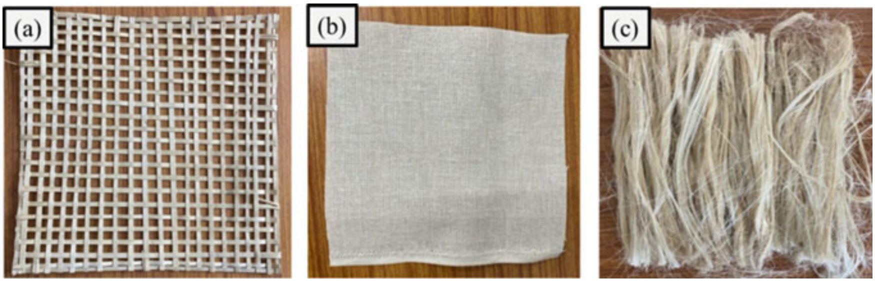


Fig. 1 Different forms of bamboo **a** strip, **b** woven mat, and **c** fibre

It is clear from the above discussion that most of the researchers focused on evaluating and improving the mechanical performance of PLA/bamboo composites consisted of bamboo fibre. However, the performance of different forms of bamboo like bamboo strip, short bamboo fibre, and bamboo in woven mat on the properties of resultant PLA/bamboo composites has not been compared and thoroughly investigated. Thus, this study presents a comparative analysis of mechanical properties (tensile and flexural) of PLA/bamboo composite composed of different form of bamboo (strip, short fibre, and woven mat). The different form of bamboo was also treated chemically to study the effect of different treatments on the mechanical performance of the engineered PLA/bamboo composite.

2 Experimentation

2.1 Materials

The pallet form of PLA used to develop the composite was collected from Natur Tec, India. Both glass transition temperature and melting temperature of the PLA are 50–80 °C and 145–180 °C whereas the density is 1.24 g/cm^3. The bamboo in various forms like strip, woven mat, and fibre was collected from Sri Lakshmi Group, AP, India as shown in Fig. 1. In this study, the chemicals used for the treatment of different forms of bamboo were supplied by Greenergy Lab Chemicals, Meghalaya, India. The double distilled water was used for cleaning the bamboo strip, woven mat, and fibre.

2.2 Chemical Treatment

The different forms of bamboo were well cleaned before performing the chemical treatment. The detergent treatment was performed to remove the unwanted residues

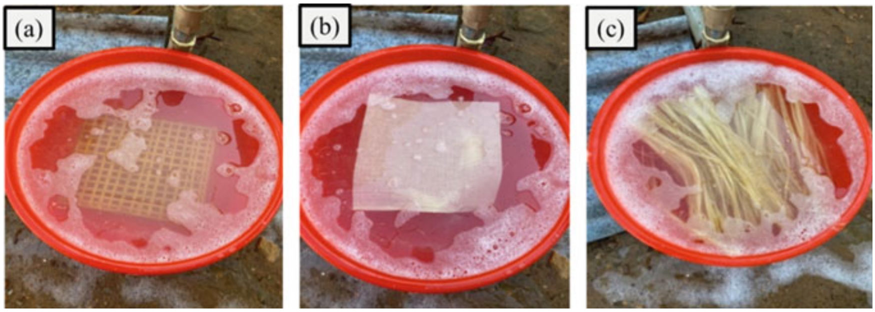


Fig. 2 Detergent treatment of different forms of bamboo **a** strip, **b** woven mat, and **c** fibre

from the bamboo strip, woven mat, and fibre. The detergent treatment was carried out for 20 min as shown in Fig. 2. The detergent solution was prepared by adding 10 gm of soft detergent to 21 L of water.

The digested debris, impurities, and dust particles were removed successfully through detergent treatment. After the detergent treatment, the bamboo was neatly cleaned with double distilled water to remove the deposited detergent on the surface of bamboo. After cleaning, bamboo strip, woven mat, and fibre were kept at room temperature until dried. Then two different types of chemical treatments (sodium hydroxide and potassium hydroxide) were performed to improve the surface characteristics of different forms of bamboo. First, bamboo was treated by using 2% (w/v) sodium hydroxide (NaOH) aqueous solution for 4 h. The potassium hydroxide (KOH) treatment was performed where the different forms of bamboo were rinsed in the KOH solution at a concentration of 1.5% (w/v) for 1 h 45 min. Vinayagamoorthy [26] also reported a similar NaOH treatment process while fabricating vetiver grass/polyester-based polymer composite by compression molding process. The authors observed that in NaOH treated vetiver/polyester composite, the fibre was properly covered with matrix material without any presence of cavities. Vinayagamoorthy and Rajeswari [27] used NaOH treated fiber to study the influence of NaOH treatment on the performance of the vetiver/jute/glass-vinyl ester-based hybrid composite. The composite was fabricated by conventional hand layup process. The results revealed that chemical treatment changed the fibre surface properties which helped to achieve better mechanical properties. After chemical treatments, the bamboo was neatly washed with double distilled water to remove the excess chemicals. Figures 3 and 4 show the chemical treatment of different forms of bamboo. The chemically treated bamboo was then kept at room temperature until dried. The dried bamboo was then kept in the oven at 60 °C to remove moisture.

Fig. 3 Preparation of chemical treatment of different forms of bamboo

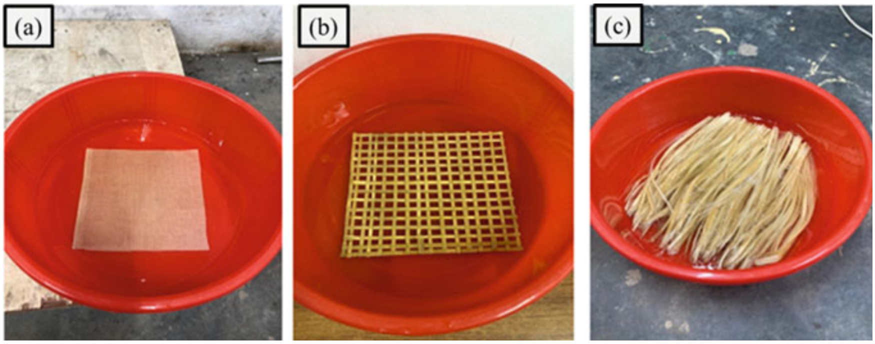


Fig. 4 Chemical treatment of bamboo **a** woven mat, **b** strip, and **c** fibre

2.3 *Composite Fabrication*

The hot-compression molding technique was applied to fabricate the PLA/bamboo green composite. During the fabrication, the mold temperature was monitored by using thermocouples (K-type). The fabrication of the green composite by film stacking method was implemented in this study. Initially, PLA pellets were kept in an oven at an elevated temperature (80 °C) to remove the moisture. After preheating the mold at the required temperature, PLA pellets were converted into thin PLA film (thickness: 1.5 mm) by compression molding. During fabricating the PLA films, the mold temperature was maintained at the melting temperature of PLA. The mold was compressed at a pressure of 3 MPa to fabricate the PLA films. After fabricating the

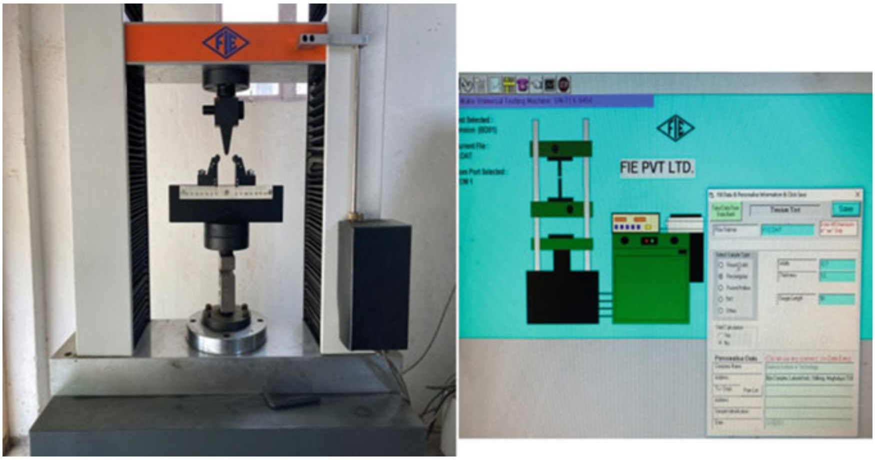


Fig. 5 Mechanical testing setup utilized to find the properties of the composite

PLA films, bamboo in different forms (strip, woven mat, and short fibre) were placed between the PLA films and compressed at 6 MPa and 180 °C. The mold was then cooled for 3 h to obtain the consolidated green composites.

2.4 Mechanical Testing

The properties of fabricated composite under tensile and flexural loadings were evaluated following ASTM standards (tensile by ASTM D-638 and flexural by ASTM D-790). The testing was carried out by using a UTM (UNITEK 9450). The maximum load capacity of the UTM is 50 kN. The gauge length and jaw speed were considered as 50 mm and 2 mm/min, respectively. The 3-point bending test was carried out to evaluate the flexural properties of the chosen test specimens. Three specimens were tested under both the loading conditions and then the average properties of the fabricated green composites were calculated. Figure 5 shows the testing setup utilized to find the properties under different loading conditions.

3 Results and Discussion

Both tensile and flexural testing was conducted to investigate the influence of different forms of bamboo and chemical treatments on the performance of engineered green composites. The chemical treatment improved the mechanical performance of the composite. The treated composite specimens performed better in terms of mechanical properties than the nontreated green composite specimens. The performance

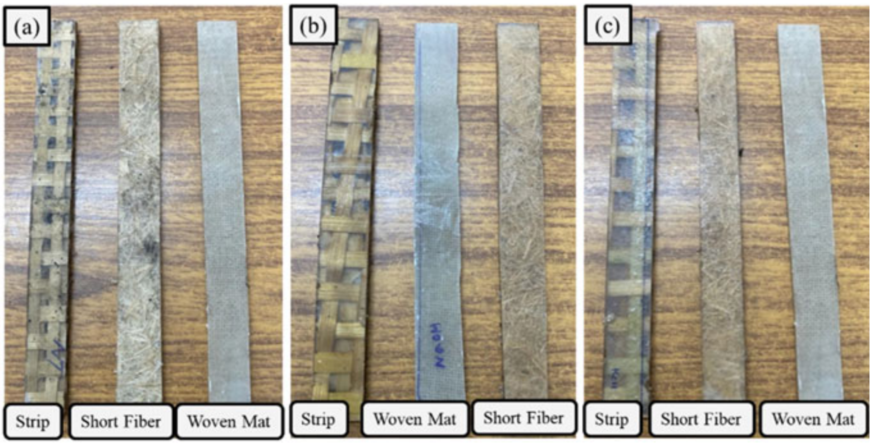


Fig. 6 Green composites specimens fabricated by using **a** nontreated bamboo, **b** treated bamboo (NaOH), and **c** treated bamboo (KOH)

of the green composite was evaluated by testing the specimens under tensile and flexural loadings. The green composites of several combinations were prepared. Figure 6a shows the green composites specimens fabricated using nontreated bamboo in different forms. Similarly, Fig. 6b, c show the green composites specimens developed by using chemically treated (NaOH and KOH) different forms of bamboo.

Table 1 shows the average tensile properties of both treated and nontreated bamboo-reinforced green composites. The average tensile strength, modulus, and percentage elongation of nontreated bamboo (strip)/PLA green composite were found as 40.62 MPa, 0.70 GPa, and 18.80%. Green composites engineered by using NaOH treated bamboo strip and PLA exhibited tensile strength, modulus, and percentage elongation of 33.49 MPa, 0.71 GPa, and 17.01%. Whereas KOH treated

Table 1 The tensile properties of treated and nontreated green composites reinforced with different forms of bamboo

Composites	Treatment type	Tensile strength (MPa)	Tensile modulus (GPa)	Percentage elongation (%)
Bamboo (strip)/PLA	Nontreated	40.62	0.70	18.80
	NaOH treated	33.49	0.71	17.01
	KOH treated	48.34	1.24	11.36
Bamboo (woven mat)/PLA	Nontreated	30.56	0.59	17.24
	NaOH treated	32.36	1.11	9.58
	KOH treated	24.38	0.71	12.66
Bamboo (short fibre)/PLA	Nontreated	13.96	0.29	15.80
	NaOH treated	15.15	0.60	8.32
	KOH treated	16.31	0.64	8.78

bamboo strip-reinforced green composites exhibited tensile strength, modulus, and percentage elongation of 48.34 MPa, 1.24 GPa, and 11.36%. The tensile strength of NaOH treated green composites decreased by 17.53% and KOH treated green composites increased by 19% as compared to the nontreated green composites. Both NaOH and KOH treatment showed an improvement in the modulus (tensile) by 1.13% and 75.53% while compared one-on-one with nontreated green composites. However, percentage elongation was decreased due to the chemical treatment as a result the green composites become more brittle. This corroborates the findings reported by Srisuk et al. [17]. The better bonding between the polymer and fibre during KOH treatment resulted in an improvement in the properties of the green composites. It can also be inferred that the green composites reinforced with bamboo strip can bear more load as compared to other developed composites. The green composites obtained by reinforcing treated (NaOH) bamboo strip exhibited higher modulus but lower in strength when compared with the nontreated bamboo strip-reinforced green composites. The decrease in the tensile strength indicates poor stress transfer between the composite constituents.

The strength, modulus, and percentage elongation obtained during tensile testing of nontreated bamboo (woven mat)/PLA green composites were 30.56 MPa, 0.59 GPa, and 17.24%. Both strength and modulus of bamboo (woven mat)/PLA green composites were improved by 5.87% and 88.10% because of NaOH treatment. The properties of the KOH treated green composites consisted of bamboo woven mat was decreased by 20.2% (strength) and increased by 20.83% (modulus) as compared to the nontreated bamboo (woven mat)/PLA green composites. In both chemical treatments, the percentage elongation of the developed green composites was decreased as chemical treatment of bamboo resulted in more rigidity of the woven mat. In NaOH treatment, the ions are separated as Na^+ and OH^- due to hydration reaction. The OH^- ions then enter in the gaps between the layers of cellulose which damage the H bonds. This leads to an increase in the active hydroxide groups. This subsequently resulted in more amorphous area. With an increase in the amorphous area of fibre, polymer penetration into the fibre is also increases. This subsequently improved the adhesion between the chosen polymer and fibre. Wang et al. [20] studied the characteristics of the chemically treated fibre. The treatment showed superior performance of the composites. The strength, percentage elongation, and modulus of the nontreated bamboo (short fibre)/PLA green composites under tensile loading were 13.96 MPa, 15.8%, and 0.29 GPa. The strength and modulus of NaOH treated bamboo (short fibre)/PLA green composites obtained during tensile testing were improved by 8.46% and 103.8% as compared to the nontreated green composites. Similarly, KOH treated bamboo (short fibre)/PLA green composites showed an increment of the tensile strength and modulus by 16.3% and 115.4%, respectively. Both NaOH and KOH treatments resulted in a decrease in the percentage elongation of bamboo (short fibre)/PLA green composites by 47.3% and 44.3%. The mechanical performance of the short fibre-reinforced green composites was relatively poor as compared to woven mat and strip-reinforced green composites. Figure 7 shows the tensile tested specimens of both treated and nontreated green composites.

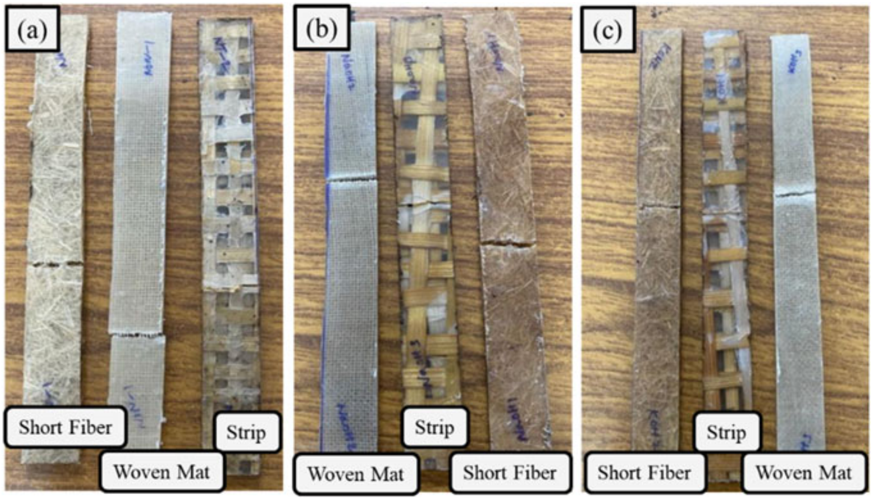


Fig. 7 Tensile tested green composites specimens **a** nontreated, **b** NaOH treated, and **c** KOH treated

Figures 8, 9 and 10 shows the overall comparisons of tensile properties of different forms of bamboo/PLA green composites. The composites reinforced with bamboo strip treated with KOH showed better properties among all the engineered green composites. The strength and modulus of KOH treated bamboo strip-reinforced with PLA obtained under tensile loading was 48.34 MPa and 1.24 GPa, respectively. The percentage elongation of the same composites was 11.36%.

Table 2 shows the properties of treated and nontreated bamboo-reinforced green composites obtained under flexural loading. The chemical treatment also resulted in an improvement in the flexural properties when compared with nontreated green composites. Initially, detergent treatment removed the impurities from fibre surface and then chemical treatment improved the bonding characteristic of the fiber which subsequently improved the adhesion between the polymer (PLA) and fibre (bamboo). The average strength, percentage elongation, and modulus of nontreated bamboo (strip)/PLA green composites obtained under flexural loading were 1.91 MPa, 13%, and 0.03 GPa. NaOH treatment of bamboo strip improved the flexural modulus and strength by 50.85% and 59.52%. Similarly, KOH treatment improved the flexural modulus and strength by 101% and 221%. The percentage elongations of NaOH and KOH treated bamboo (strip)/PLA green composite were 19.17% and 5.56%.

The green composites composed of nontreated bamboo woven mat and PLA exhibited the strength of 2.4 MPa, percentage elongation of 7.59%, and modulus of 0.1 GPa, under flexural loading. The strength and modulus of NaOH treated bamboo (woven mat)/PLA green composites were increased by 51.31% and 60.87% as compared to nontreated green composites. Similarly, the strength and modulus of KOH treated composites was improved by 66.7% and 201%, respectively. The percentage elongation of NaOH and KOH treated bamboo (woven mat)/PLA green composites was 7.1% and 4.41%, respectively. The strength, percentage elongation,

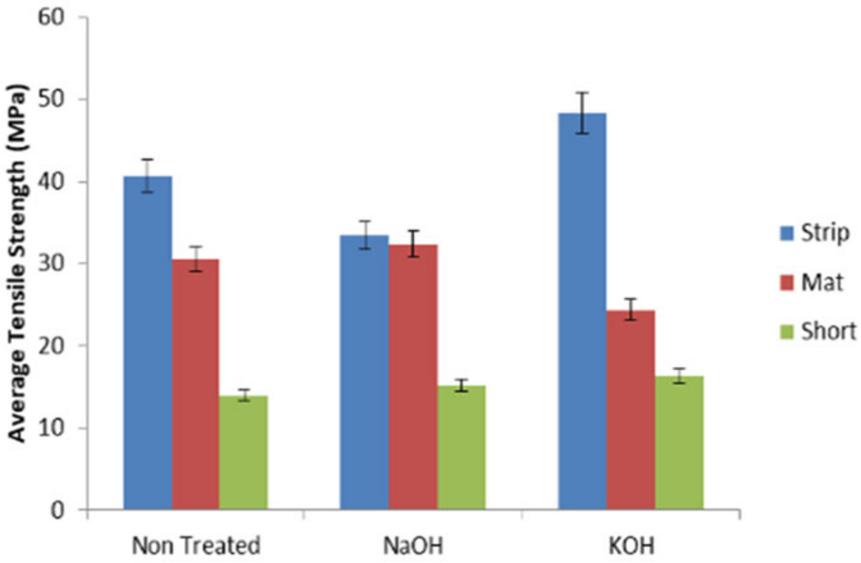


Fig. 8 Comparisons of tensile strength of the engineered composites

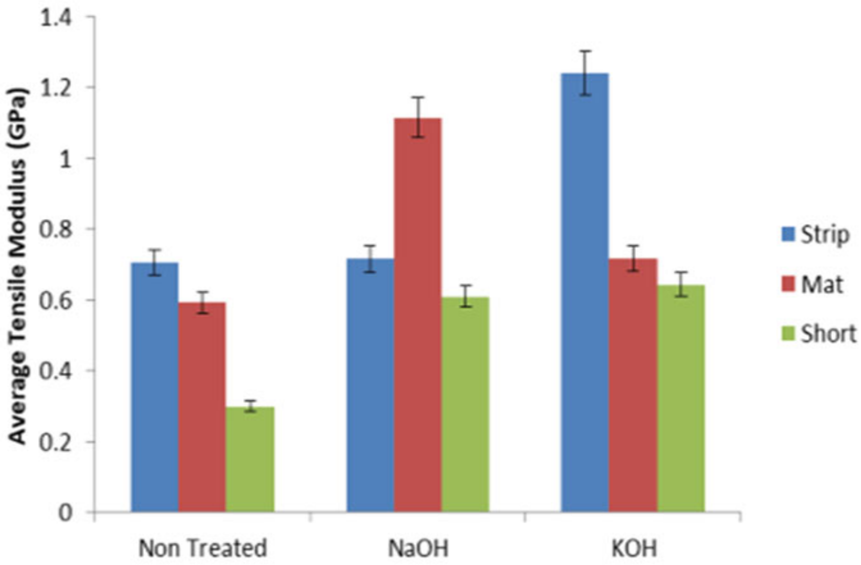


Fig. 9 Comparisons of tensile modulus of the engineered composites

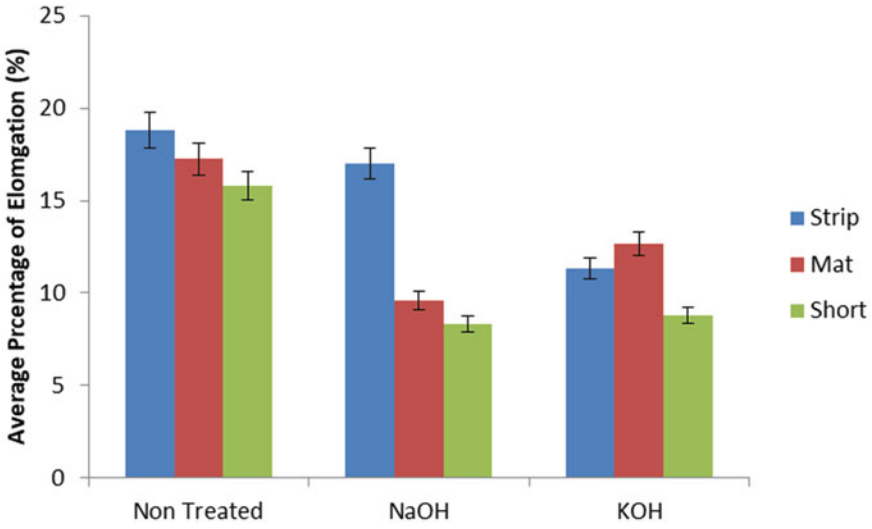


Fig. 10 Comparisons of percentage elongation of the engineered composites

Table 2 The flexural properties of treated and nontreated green composites reinforced with different forms of bamboo

Composites	Treatment Type	Flexural Strength (MPa)	Flexural Modulus (GPa)	Percentage Elongation (%)
Bamboo (strip)/PLA	Nontreated	1.91	0.03	13.0
	NaOH treated	3.05	0.05	19.17
	KOH treated	6.15	0.38	5.56
Bamboo (woven mat)/PLA	Nontreated	2.40	0.10	7.59
	NaOH treated	3.64	0.16	7.10
	KOH treated	4.01	0.31	4.41
Bamboo (short fibre)/PLA	Nontreated	2.52	0.11	7.43
	NaOH treated	2.02	0.03	7.92
	KOH treated	2.18	0.18	3.87

and modulus of nontreated bamboo (short fibre)/PLA composites obtained under flexural loading were 2.52 MPa, 7.43%, and 0.11 GPa. The chemical treatment of the short fibre resulted in deterioration in the flexural properties. The flexural strength decreased by 19.8% and 13.5% due to NaOH and KOH treatment. The flexural modulus of NaOH treated bamboo (short fibre)/PLA green composites was decreased by 69.5% whereas KOH treatment showed an improvement in the flexural modulus by 3.5% as compared to nontreated green composites. The percentage elongation of NaOH and KOH treated green composite was 7.92% and 3.87%. Figure 11 shows the flexural tested specimens of both treated and nontreated green composites.

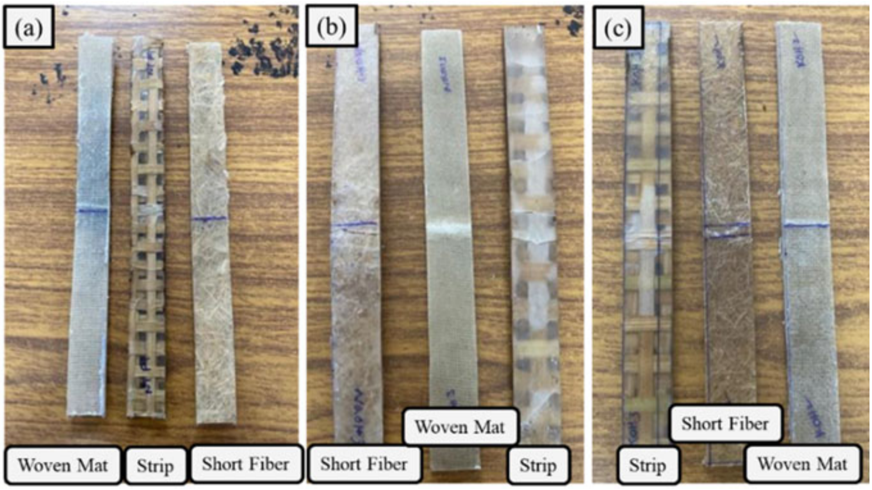


Fig. 11 Flexural tested green composites specimens **a** nontreated, **b** NaOH treated, and **c** KOH treated

The chemical treatment of bamboo strip and woven mat resulted in improvement in flexural properties of the composites as compared to the nontreated bamboo-reinforced composites. NaOH treatment changed the surface structure of bamboo. The compact fibril structure of the bamboo surface was turned into a less dense structure by controlling the hydrogen bonds in the cellulose through depolymerizing. The chemical treatment mainly removes the impurities as a result the porosity of the bamboo was increased. This change in the bamboo structure allowed strong bonding between the polymer and fibre. As a result, the load bearing capacity of the composites was improved. However, the properties of the treated composite composed of short fibre obtained under flexural loading were not good enough in comparison to the nontreated green composites. In this case, the chemical treatment is less efficient in enhancing the interfacial bonding between the constituents of composites.

Figures 12, 13, 14 show the overall comparison of flexural properties of different forms of bamboo-reinforced green composites. The green composites composed of KOH treated bamboo strip and PLA exhibited better flexural properties among all the engineered green composites. Both chemical treatments showed some improvement in the properties when compared with nontreated green composites. The result of the present study has also been compared with previous studies to understand the improvement in mechanical performance of the engineered green composites. From the comparative analysis, it can be inferred that the present experimental values are in close agreement with the previous studies. Table 3 shows the mechanical properties of different bamboo/PLA green composites obtained through different treatments.

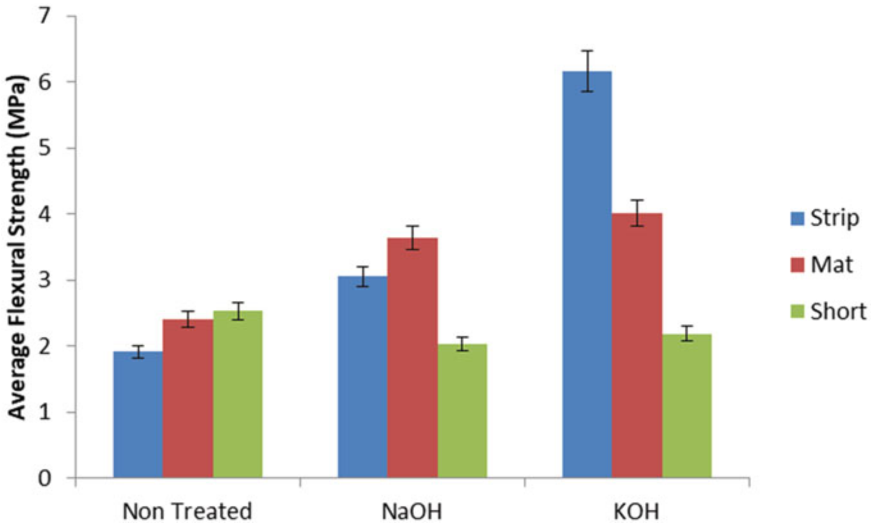


Fig. 12 Comparisons of flexural strength of the engineered composites

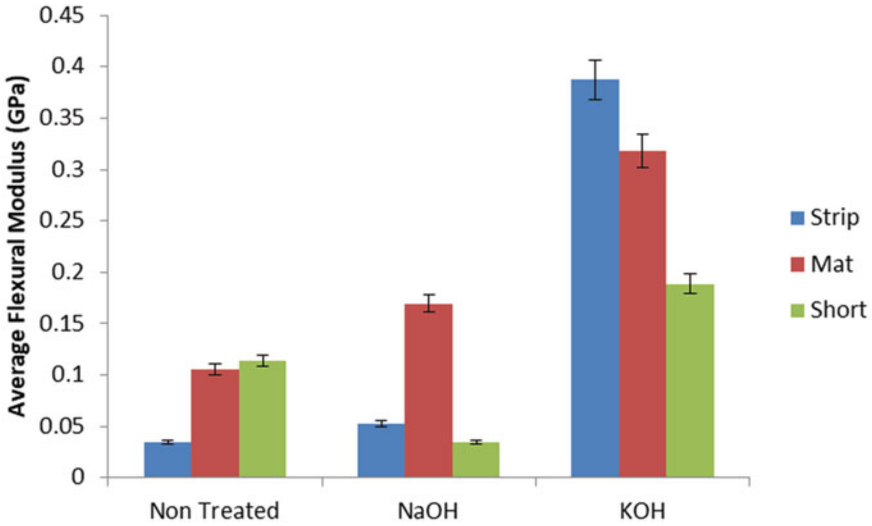


Fig. 13 Comparisons of flexural modulus of the engineered composites

4 Conclusions

In this study, bamboo fibres in a different form (strip, woven mat, and short fibre) were chemically modified by implementing different chemical treatments like NaOH and KOH treatments. The effect of chemical treatment was investigated in terms of

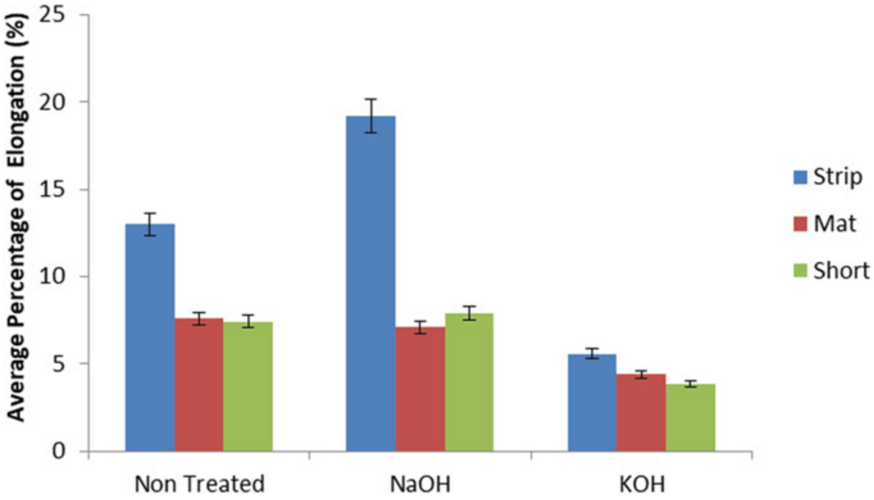


Fig. 14 Comparisons of percentage elongation of the engineered composites

Table 3 Comparison of mechanical properties of bamboo/PLA green composites

Composites	Treatment	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Reference
Bamboo (strip)/PLA	KOH	48.34	1.24	6.15	0.38	present study
Bamboo (woven mat)/PLA	NaOH	32.36	1.11	3.64	0.16	present study
Bamboo (short fibre)/PLA	KOH	16.31	0.64	2.18	0.18	present study
Bamboo (woven mat)/PLA	–	48.72 ± 2.48	0.983 ± 0.045	104.82	2.29	[5]
Bamboo (short fibre)/PLA (NCO 0.33%)		42	2.964	–	–	[9]
PLA-g-BF (Bamboo Fibre)	–	19.4	5.1	–	–	[11]
Bamboo (particle)/PLA/ultrafine bamboo-char (5.0 wt.%)		45.2	0.54	–	–	[16]
Bamboo (particle)/PLA	NaOH	44.21	0.406	83.85	4.50	[18]

mechanical performance. The performance of the green composite developed by reinforcing different form of bamboo was evaluated by performing mechanical testing under tensile and flexural loadings. The properties of the treated bamboo-based composites obtained under tensile and flexural loadings were compared with the nontreated composites. KOH treated bamboo (strip)/PLA green composites exhibited better properties among all the developed composites. Both modulus and strength of the green composites under tensile loading were improved by 19% and 75.53% when compared with nontreated bamboo (strip)/PLA green composites. Whereas the properties of bamboo (woven mat)/PLA green composites were better under NaOH treatment than the nontreated bamboo (woven mat)/PLA green composites. The properties of bamboo (short fibre)/PLA green composites were slightly improved through chemical treatment.

Acknowledgements The corresponding author is thankful to the State Council of Science, Technology & Environment (SCSTE), Meghalaya, for financially supporting this work.

References

1. Choudhury MR, Debnath K (2020) Experimental analysis of tensile and compressive failure load in single-lap adhesive joint of green composites. Int J Adhesion Adhesives, 99, 102557
2. Singhal AV, Debnath K, Singh I, Daniel BSS (2016) Critical parameters affecting mechanical behavior of natural fiber reinforced plastics. Journal of Natural Fibers 13(6):640–650
3. Varshney D, Debnath K, Singh I (2014) Mechanical characterization of polypropylene (PP) and polyethylene (PE) based natural fiber reinforced composites. International Journal of Surface Engineering & Materials Technology 4(1):16–23
4. Rawi NFM, Jayaraman K, Bhattacharyya D (2013) A performance study on composites made from bamboo fabric and poly (lactic acid). J Reinf Plast Compos 32(20):1513–1525
5. Porras A, Maranon A (2012) Development and characterization of a laminate composite material from polylactic acid (PLA) and woven bamboo fabric. Compos B Eng 43(7):2782–2788
6. Sukmawan R, Takagi H, Nakagaito AN (2016) Strength evaluation of cross-ply green composite laminates reinforced by bamboo fiber. Compos B Eng 84:9–16
7. Wang YN, Weng YX, Wang L (2014) Characterization of interfacial compatibility of polylactic acid and bamboo flour (PLA/BF) in biocomposites. Polym Testing 36:119–125
8. Kang JT, Kim SH (2011) Improvement in the mechanical properties of polylactide and bamboo fiber biocomposites by fiber surface modification. Macromol Res 19(8):789–796
9. Lee SH, Wang S (2006) Biodegradable polymers/bamboo fiber biocomposite with bio-based coupling agent. Compos A Appl Sci Manuf 37(1):80–91
10. Kumar V, Sharma NK, Kumar R (2013) Dielectric, mechanical, and thermal properties of bamboo–polylactic acid bionanocomposites. J Reinf Plast Compos 32(1):42–51
11. Li W, He X, Zuo Y, Wang S, Wu Y (2019) Study on the compatible interface of bamboo fiber/polylactic acid composites by in-situ solid phase grafting. Int J Biol Macromol 141:325–332
12. Kobayashi S, Takada K, Song DY (2012) Effect of molding condition on the mechanical properties of bamboo-rayon continuous fiber/poly (lactic acid) composites. Adv Compos Mater 21(1):79–90
13. Fazita MRN, Jayaraman K, Bhattacharyya D, Hossain MdS, Haafiz MKM, Khalil HPSA (2015) Disposal options of bamboo fabric-reinforced poly (lactic) acid composites for sustainable packaging: Biodegradability and recyclability. Polymers 7(8):1476–1496

14. T. Chen, Y. Wu, J. Qiu, M. Fei, R. Qiu, W. Liu (2020), Interfacial compatibilization via in-situ polymerization of epoxidized soybean oil for bamboo fibers reinforced poly (lactic acid) biocomposites. Composites Part A: Applied Science and Manufacturing, 138, 106066.
15. Dehghan M, Faezipour M, Azizi M, Hosseinabadi HZ, Bari E, Nicholas DD (2019) Assessment of physical, mechanical, and biological properties of bamboo plastic composite made with polylactic acid. Maderas. Ciencia y Tecnología 21(4):599–610
16. Qian S, Tao Y, Ruan Y, Lopez CAF, Xu L (2018) Ultrafine bamboo-char as a new reinforcement in poly (lactic acid)/bamboo particle biocomposites: The effects on mechanical, thermal, and morphological properties. J Mater Res 33(22):3870–3879
17. Srisuk R, Techawinyutham L, Koetniyom W, Dangtungee R (2019) Mechanical properties of bamboo charcoal (BC)/poly (lactic) acid (PLA) composites. Key Eng Mater 801:121–126
18. Qian S, Mao H, Sheng K, Lu J, Luo Y, Hou C (2013) Effect of low-concentration alkali solution pretreatment on the properties of bamboo particles reinforced poly (lactic acid) composites. J Appl Polym Sci 130(3):1667–1674
19. Lin J, Yang Z, Hu X, Hong G, Zhang S, Song W (2018) The effect of alkali treatment on properties of dopamine modification of bamboo fiber/polylactic acid composites. Polymers 10(4):403
20. Wang F, Zhou S, Yang M, Chen Z, Ran S (2018) Thermo-mechanical performance of polylactide composites reinforced with alkali-treated bamboo fibers. Polymers 10(4):401
21. Zuo Y, Chen K, Li P, He X, Li W, Wu Y (2020) Effect of nano-SiO_2 on the compatibility interface and properties of polylactic acid-grafted-bamboo fiber/polylactic acid composite. Int J Biol Macromol 157:177–186
22. Rizal S, Saharudin NI, Olaiya NG, Khalil HPS, Haafiz MK, Ikramullah I, Yahya EB (2021) Functional properties and molecular degradation of schizostachyum brachycladum bamboo cellulose nanofibre in PLA-Chitosan bionanocomposites. Molecules 26(7):2008
23. M.J. Nurnadia, M.R. Fazita, H.P.S. Abdul Khalil, M.K. Mohamad Haafiz (2017), Optimisation of mechanical properties of bamboo fibre reinforced-PLA biocomposites. In American Institute of Physics Conference Series, Vol. 1901, 030019.
24. Ochi S (2015) Flexural properties of long bamboo fiber/PLA composites. Open Journal of Composite Materials 5(03):70
25. Qian S, Mao H, Zarei E, Sheng K (2015) Preparation and characterization of maleic anhydride compatibilized poly (lactic acid)/bamboo particles biocomposites. J Polym Environ 23(3):341–347
26. Vinayagamoorthy R (2019) Influence of fiber surface modifications on the mechanical behavior of vetiveria zizanioides reinforced polymer composites. Journal of Natural Fibers 16(2):163–174
27. Vinayagamoorthy R, Rajeswari N (2014) Mechanical performance studies on vetiveria zizanioides/jute/glass fiber-reinforced hybrid polymeric composites. J Reinf Plast Compos 33(1):81–92

Optimization of Process Parameters in AWJ Cutting of Pineapple Fiber Reinforced Polymer Composites: Hybrid SCCSA Algorithm

A. Tamilarasan, T. Rajmohan, D. Rajamani, and K. Palanikumar

Abstract The present study aims to prepare Pineapple Fiber Reinforced Polymer Composite. The kerf taper angle is then measured by cutting the composite with an abrasive water jet. The primary goal is to reduce the kerf taper angle in order to optimize machining performance. In this way, mathematical model was first developed by employing experimental approaches, beginning with the design plan called box-Behnken using response surface technique. The model's predicted values were found to be reasonably close to the actual experimental values. Then, a hybrid SCCSA algorithm has been utilized for optimizing the AWJ process parameters by single objective optimization is considered, and optimal value is determined. The results indicated that the SCCSA optimization strategy is a viable and effective method for optimizing the AWJ cutting process.

Keywords AWJ cutting · Composite · SCCSA algorithm · Optimization

1 Introduction

There is a great demand for cheap, environmentally-friendly, high quality that can save cost without sacrificing important attributes [1]. The materials science community is continuously involved in developing novel materials with improved properties to meet needs of emerging technologies in many industrial applications [2]. Natural fiber enhanced polymer composite applications, because of their bio-degradable nature, show an enormous development rate in global market. In this scenario,

A. Tamilarasan (✉) · T. Rajmohan
Centre for Composite Science and Tribology, Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya, Kanchipuram 631 561, India

D. Rajamani
Department of Mechanical Engineering, Vel Tech Rangarajan Dr, Sagunthala R&D Institute of Science and Technology, Chennai 600062, Tamilnadu, India

K. Palanikumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, Chennai 600 044, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_7

machining is the only recommended way of generating holes and other needs [3]. It is difficult to manufacture fiber composites due to the fact that the composite cutting process is distinct from that of traditional materials. In the typical machining technique, the fiber refinement may produce additional tool wear, leading to serious damage to the material. Compared to synthetic fibers, the production costs of Natural Fiber Composites (NFCs) are lower, and the equipment needed to create them is less wearable [4]. The market for these composites is rapidly increasing as prospective substitutes for inorganic or synthetic materials across a wide range of applications, including tooling, automotive, railroad sleepers, packaging, and shelving, industries of construction. The tool constantly encounters filler and matrix materials, and the varied force causes quick tool wear, work material damage (fiber full out, delamination, and poor hole quality), and low productivity. To address these obstacles, novel machining technologies Several techniques were used, including AWJ, UJM, WEDM and laser cutting.

Water jet abrasive machining (AWJ) uses high-velocity streams of water to accelerate abrasive particles for material removal [5]. Water jet technique is suitable for cutting fiber reinforced composites due to its special qualities. These industries have attached great importance to abrasive water jet technology due to the unique advantages it offers when processing composite materials (e.g. Tools do not get damaged by heat, cutting pressures are not excessive, and production is high) [6]. This approach has been shown to be a practical means of fabricating composite materials. Water jet cutting allows for the configuration of a wide variety of machining parameters, including water pressure, nozzle distance, cutting speed, and nozzle diameter. These process parameters are more crucial in AWJM composites than grain size, mass flow rate, and angle of contact for abrasive particles because of the type and amount of abrasives being utilized [7]. Delamination, on the other hand, is the most prevalent composite problem when it comes to machining composites, which are largely laminated composites. The effect of shock waves on the surface of the material during the preliminary cutting stage of employing AWJM to cut composites causes crack spots to form in the work piece material during the cutting process. Now, the high-pressure AWJM reaches the fracture points, resulting in a water hammering effect. Indeed, the success of the machining process is contingent upon making a rational decision based on cost and quality considerations. Then, a critical difficulty in the AWJ cutting process is determining an accurate result for assessing machining performance parameters such as kerf taper angle and surface roughness. The machine operator is able to choose the conditions of cutting during the machining process. Researchers recently presented extensive assessments of new evolutionary algorithms for prediction and optimization challenges. Over the last decade, meta-heuristic optimization strategies have attracted researchers' attention. ACO, PSO and GA are examples of such techniques. These techniques have been used in a variety of engineering domains, in addition to extensive theoretical research. The reason that such algorithms have grown so popular in terms of application to engineering issue solving is due to four primary characteristics: Simplicity, versatility, a derivation-free method, and the avoidance of local optima. Meta-heuristic algorithms, in general, are pretty straightforward in their application because they have been inspired by simple concepts throughout the majority of their existence. The inspirations are drawn from natural occurrences such as animal behavior and evolutionary concepts. This simplicity enables the simulation of various natural concepts, the development of novel meta-heuristics, the hybridization of two or more meta-heuristics, and even the enhancement of existing ones.

2 State of the Art

Shukla and Singh [7] attempted to optimize characteristics of performance (kerf width-top and taper angle) and processing parameter ranges such as standoff distance, transverse speed and mass flow rate for the AWJ cutting process. Seven optimization approaches are used to do this, including the FA, PSO, ABC, black hole, SA, biogeography, and NSGA-II. Comparing the effectiveness of various algorithms reveals that the biogeography algorithm outperforms the others. The use of the NSGA to analyze both objectives simultaneously is attempted. With the NSGA technique, it is possible to generate a collection of one hundred solutions that are not skewed in the direction of the region of the control factors under consideration. Results produced through the use of NSGA are extremely consistent with those acquired experimentally. Zain et al. [8] have used these techniques in order to determine the most suitable process parameters for waterjet cutting. In some cases, genetic algorithm techniques were used to determine ideal process parameters, which resulted in the best possible water jet cutting performance with the least amount of machining required. All of the following are considered process variables: standoff distance, water jet pressure, abrasive grit size, and traverse speed for AWJ machining. Extracted from the work, it concluded that integrated SA–GA–type2 is acceptable for identifying the optimum process parameters. The study's findings were supported by comparison to real-world experimental data, demonstrating that both proposed integration systems were capable of computing the optimal values, resulting in the lowest possible value of machining performance. Using a GWO optimization tool, Chakraborty and Mitra [9] were able to achieve success in the parametric optimization of the AWJ process, which was previously unexplored. Results from single- and multi-objective optimization problems using GWO vs. SA, GA, and TLBO algorithms also it is revealed that the results provided by GWO are quite good. The generated scatter diagrams depicting the response of various AWJM process parameters to changing values will assist process engineers and operators can assist in optimizing those settings for maximum machining performance. Jagadeesh et al. [10] conducted studies on three laminates of variable thicknesses, adjusting input factors such as traversal rate and standoff distance. The impact each input's parameter on responses like kerf taper and surface roughness was investigated using a response surface technique and analysis of variance. The ideal parameters that result in the the finest machining quality was determined using numerical and graphical optimization techniques. The researchers noticed that increasing the traverse rate resulted in an increase in the surface roughness and taper angle of the cut kerf on the cut surface, as well as an increase in the surface roughness of the cut surface. As a result, where machining quality is essential, a lower traverse rate is better. Dhakal et al. (2018) used abrasive water jet drilling to investigate the effect of traverse speed variation on machining-induced damage to fiber-reinforced composites. The vacuum bagging procedure was used to fabricate three distinct types of epoxy-based composite laminates: flax fibers that are unidirectional, carbon fiber-reinforced composites, and hybrid carbon-flax fibers. Surface roughness and damage reactions generated by delamination drilling were shown to be significantly influenced by traverse speed, according to the research findings. Indeed, increasing the water jet's traverse speed did seem to boost the damage responses in the three samples.

Abrasive waterjet machining of a 7075 aluminum metal matrix composite was investigated by Shanmugam et al. [12]. The responses surface approach and ANOVA were used to find the effect of process factors on both taper angle and surface roughness. The speed and pressure of the jet traversal were the most essential process factors since they determined the roughness of the surface and the taper angle, respectively. The roughness of the surface and the taper angle of the jet are raised by raising the pressure and traversal speed of the jet. Simultaneously, lowering the standoff distance and increasing the speed of the jet traverse could increase both reactions. Rao [13] synthesized carbon, glass, and carbon-glass fiber-reinforced polymer composites for use in abrasive water jet machining. The machining tests are conducted to ascertain the effect of the primary machining parameters, on the intended machining properties, namely surface roughness, kerf top width, and material removal rate, the cutting speed, feed rate, and stand-off distance are dependent.). A multi-objective optimization process known as the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is then used to optimize the equations, with the three equations Ra, kw, and MRR being used to establish the three objectives of a multi-objective optimization problem (MOOP). Tripathi [14] established the effect of AWM variables on GFRP composites. Cutting speed and abrasive flow rate are employed as input factors, whilst roundness, MRR, cylindricity and surface roughness are used as outcome qualities within that experiment. The effectiveness of recently developed optimization algorithms (Rao 1–3) was also investigated in parametric optimization of waterjet abrasive machining variables, and the results were compared to those obtained using established parameter-free optimization methods, such as JAYA and TLBO. It has been noticed that the aforementioned techniques use significantly less computation time and iterations. These recently discovered population-based methods are straightforward and straightforward to implement in optimization applications. Thamizhvalavan et al. [15] described the research on the machinability of aluminum hybrid composites with varying compositions via an abrasive water jet machining technique. Stir casting was utilized to fabricate aluminum hybrid metal matrix composites containing 5% Zirconium Silicate ($ZrSiO_4$) and 5, 10, and 15% Boron Carbide (B_4C).During the cutting studies, it was revealed that altering the traverse rate and abrasive flow rate, as well as the abrasive mesh size, all had an effect on cutting depth, MRR, and surface roughness. The Box-Behnken response surface approach was used to construct the investigations, and response surface plots were used to analyze the data. Aluminum hybrid composites were shown to be suitable for machining with higher depths of cut and material removal rates while using it has 100 MPa of water jet pressure and has a traverse rate of 120 mm/min. Additionally, in all types of hybrid composites, the abrasive mesh size 100 influenced the creation of a smoother surface. The examined literature demonstrates a consensus regarding the usage of RSM for assessing various response characteristics in AWJ machining operations. It has been claimed that just a few attempts have been made to design a hybrid optimization algorithm for optimizing the process parameters in AWJ cutting process.

The present work assesses the Abrasive water jet cutting performance of pineapple fiber reinforced polymer composites for minimizing the taper angle. Four important parameters have been investigated and modeled for kerf Taper angle using response surface methodology (RSM). Experimental data were acquired through the use of a box Behnken design in order to construct mathematical models for input variables and output cutting characteristics. Then, the Sine Cosine Crow Search Algorithm (SCCSA) is implemented for obtaining the minimal values of kerf taper angle.

3 Box-Behnken Design

Experiment design plays an important role for efficiency, accuracy in analysis, and cost savings. The primary purpose of response surface methodology is to identify how different AWJ cutting parameters affect output quality attributes [16–23]. RSM is used to express quantitative relationships between cutting parameters and output quality aspects in the form of the a second-order polynomial regression model:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon$$

Here, $y$denotesis the response and x_{i}denotes the ith AWJ cutting parameter value; $\beta_0$indicates the model constant; $\beta_i$symbolizes the linear coefficient; β_{ii} signifies the quadratic coefficient; β_{ij}stands the coefficient for interactionand ε is the experimental error. Lastly, the $k$indicaates the number process variables involved the process. Box–behnken design was chosen for 29 sets of experimental design, based on the response surface approach. Using Design-Expert 7 software, the BBD, the most effective RSM with the fewest experiments, was utilized to plan the experiment.

4 Development of Composites and Experimentation

The pineapple (Ananascomosus) is one of the most commonly cultivated fruits in the world. Therefore, pineapple leaves can be used to manufacture natural fibers, which are inherently considered to be waste products. It can be utilized in a variety of applications such as artificial fibers, as a sound absorber and thermal insulator, and so on. Compression moulding machine was used to fabricate the pineapple fiber-reinforced polyester composite. The PALF slashed their ideal length of 30 mm and then rinsed with water to remove any remaining residue.Then, dried in the air for final preparation the composite. The high impact polystyrene mats were cut to fit the dimensions of the mold cavity. To create layers of fiber matsand the resin mixture was put inside the moldalternately, piling them one after the other.To get a 3 mm thick plate, the split mold has to be closed with 15 MPa pressure. Finally, the mold containing the composite was held at room temperature for 24 h under steady pressure to allow it to cure properly. Around the mold cavity, the composite laminate was removed with the use of Mansion Wood Polishing (White) Wax.To ascertain the desired response, a series of tests was undertaken utilizing the RSM methodology.The Box–Behnken design technique was used to assign each factor to one of three magnitude values that were equally distant from one another. Certain design parameters were altered within each block so that they could be explored in all possible configurations, while others were kept at their initial settings.

The 3-axis AWJ machine was fitted with an ultra-high-pressure pump (Model: Water Jet Germany) and an integrated auto abrasive delivery system capable of continuously delivering abrasives for 500–800 min. The bed is 3000 mm in length by 1500 mm in width. AWJM considered a number of machine variables like traverse rate, jet pressure, abrasive mass flow rate, and stand-off distance. As shown in Fig. 1(cutting zone), all cutting operations were carried out utilizing single pass

Fig. 1 The cutting zone of AWJ process

Fig. 2 Cut section of composite

cutting in the longitudinal direction. Three slots with a length of 50 mm were cut under the same machining conditions, and in which the kerf taper has an average value measure was taken. The bottom and top widths of each through-cut slot were measured using a Video Measuring System (VMS). Vertical orientation of the composite plate was used to concentrate the slot on the top surface. For each experimental run, the kerf taper was averaged over three slots [19–21]. Figure illustrates the kerf width measurement used to calculate the kerf taper angle (Ta). Further, the kerf angle was computed using the formula below. The transverse speed was shown to be more important than water pressure and SOD in all three machining characteristics. Filler reinforcement improves machining performance, resulting in better surface quality and decreased kerf. The cut profile of an AWJ-machined workpiece is depicted in Fig. 2. It is demonstrated here how an AWJ through cut was made on the material where the top kerf wider than the kerf at the bottom and the material will have kerf taper as a result to provide the best possible cut quality, keep the taper to a minimum.

5 Statistical Modelling of Experimental Work

Experiments are conducted in the run sequence specified for the designed combination of various input parameters, and the output response as illustrated in Table 1, the kerf taper angle is obtained.I t is necessary to model the AWJ process and determine the relationship between variables and responses through the use of regression analysis. Further, the regression analysis was performed, and the quadratic model produced from the experimental data for getting kerf taper angle(KTA) through AWJ process as given in Eq. (2).

Table 1 Controllable parameters and results

Exp. Run	Jet pressure (Mpa)	Abrasive mass flow rate(g/min)	Traverse rate (mm/min)	Stand-off distance (mm)	Kerf taper angle (degrees)
1	250	700	150	1	0.6552
2	300	800	100	2	0.5822
3	300	700	150	2	0.6093
4	250	700	100	2	0.7082
5	250	600	50	2	0.7221
6	200	800	100	2	0.7059
7	250	800	100	3	0.7439
8	250	800	50	2	0.6877
9	300	700	100	1	0.6652
10	250	700	150	3	0.6773
11	250	700	50	1	0.6765
12	250	700	100	2	0.7166
13	200	700	100	3	0.8374
14	200	700	50	2	0.7748
15	250	700	100	2	0.7182
16	200	700	150	2	0.7102
17	250	700	100	2	0.7102
18	250	600	150	2	0.6988
19	300	600	100	2	0.6461
20	200	700	100	1	0.6463
21	250	600	100	1	0.7439
22	300	700	50	2	0.6315
23	300	700	100	3	0.5641
24	250	700	100	2	0.7166
25	250	800	150	2	0.6309
26	200	600	100	2	0.7685
27	250	800	100	1	0.5641
28	250	700	50	3	0.7439
29	250	600	100	3	0.6758

$$\begin{aligned} KTA = {} & -0.18778 + 5.46365E-003 \times A \\ & +1.08900E-003 \times B + 1.05553E-003 \times C \\ & +0.036280 \times D + 4.24011E-006 \times AC - 1.46036E \\ & -003 \times AD - 1.67315E-006 \times BC + 6.19640E \\ & -004 \times BD - 2.26646E-004 \times CD - 8.41651E \\ & -006 \times A^2 - 1.74616E-006 \times B^2 - 4.57887E \\ & -006 \times C^2 - 0.014501 \\ & \times D^2 \left(R^2 = 0.9977;\ R^2_{Adj} = 0.9956;\ R^2_{Pred} = 0.991\right) \end{aligned} \tag{2}$$

It is computed that R^2 values were 0.96977 for kerf taper angle, which means that 95% of experimental data were appropriate. The greater the R^2 coefficient, the more accurate the model is for the experimental data.The high adjusted R^2 value (0.9956) suggests that the predicted vs. experimental values are highly correlated.It is reasonable to expect that the predicted R-squared of 0.991 will be in close to with the adjusted R-squared of 0.9956. This indicates that developed models fit the data for both output quality characteristics effectively.

6 Sine Cosine Crow Search Algorithm

6.1 SCA Algorithm

A mathematical motivation focused on the trigonometric functions of the sine and cosine is proposed in 2016 by Mirjalili [24]. With the help of the following formula, The SCA repositions the particles within solution space to the optimal position [24].

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times \left| r_3 P_i^t - X_i^t \right|, & r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times \left| r_3 P_i^t - X_{ii}^t \right|, & r_4 \geq 0.5 \end{cases} \tag{3}$$

Where X_i^t position at which it stands, P_i^t is the best solution position and r_1,r_2, and r_3 numbers are produced randomly between zero and one. r_1 demonstrates the direction for the update, r_2 defines the distance for the update, r_3 guarantees a proper balance between emphasis and desalination by creating a random weight, and r_4 chooses a movement of the sine or cosine [24].The difference between the motions in the sine and cosine is shown in Fig. 3.

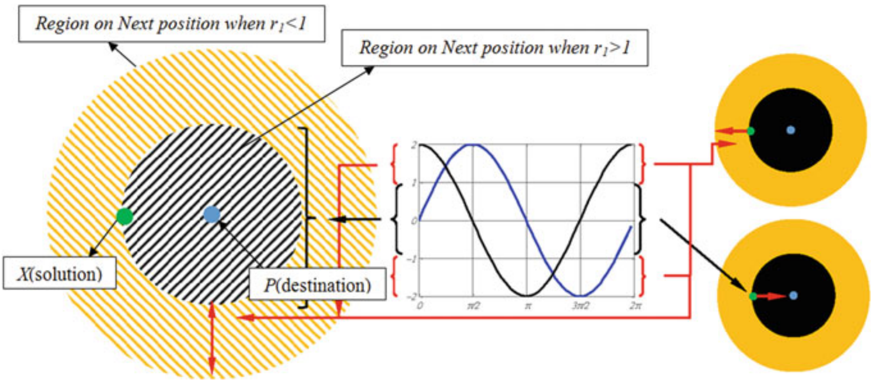


Fig. 3 The Sine Cosine Algorithm's fundamental principle [24]

6.2 Crow Search Algorithm

Crow Search Algorithm (CSA) was devised by Askarzadeh and is a population-dependent metaheuristic optimization technique. This method simulates the cognitive behavior of crows in a computer environment. This algorithm is predicated on the concealment of the surplus food stock. Crow is moral in stealing food from other birds. Keep watching other birds find out where they are hiding their food [25]. This would allow crow to take food from other birds if they left the hiding place. This action has encouraged by crows to develop algorithm called the crow-search algorithm [25]. Due to various awareness of other birds, crows change the location on the basis of the following formula [25].

$$X_i^{t+1} = \begin{cases} X_i^t + r_i \times fl_i^t \times \left|m_i^t - X_i^t\right|, & r_i < AP_i^t \\ randomposition & otherwise \end{cases} \quad (4)$$

where AP_i^t is the jth crow's consciousness. When the victim bird realizes the crow i follow, it tries to get the crow to a random place. Keep in mind that a crow j is randomly chosen for each crow I to change crow ith location. In accordance with the characteristics of length of a crow flight during the search process, as depicted in Fig. 4 [25].

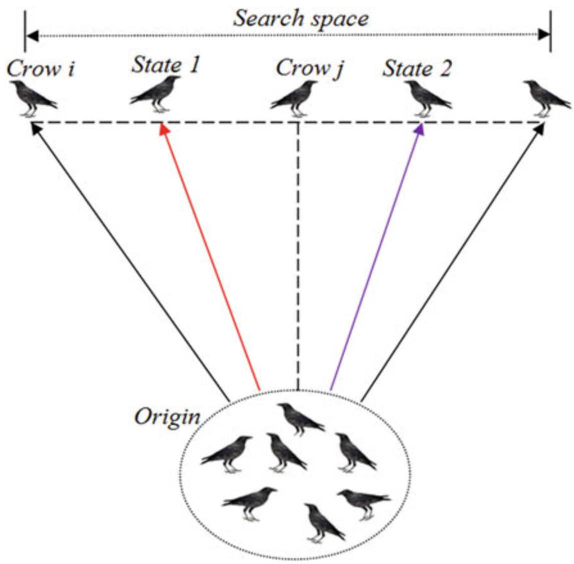


Fig. 4 Crow flight length and search [25]

6.3 Hybrid SCCSA Algorithm

The CSA is used as the primary consideration in the hybrid algorithm. According to the CSA, the fundamental disadvantage is that the search agents do not always select the most optimal solution they have ever found for a specific problem. Further, if $r_i \leq AP_i^t$ is implemented, the search agents change their location because it is assigned to a random location in solution space, which affects the CSA's efficiency [26]. Therefore, first of all, it is considered in order to improve the efficiency of CSA to update and solution to the best solution to date or on the basis of the random status of the search agent as follows [26].

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times \left|r_3 P_i^t - X_i^t\right|, & r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times \left|r_3 P_i^t - X_{ii}^t\right|, & r_4 \geq 0.5 \end{cases} \tag{5}$$

Where r_1 is a 0 to 1. Then, a SCA motions or the CSA update procedure can be used by each search agent to update its position accordingly [26].

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times \left|r_3 P_i^t - X_i^t\right|, & r_4 < 0.3 \\ X_i^t + r_1 \times \cos(r_2) \times \left|r_3 P_i^t - X_i^t\right|, & 0.3 \leq r_4 \leq 0.6 \\ X_i^t + r_1 \times fl_i^t \times \left|m_i^t - X_i^t\right|, & r_4 \geq 0.6 \end{cases} \tag{6}$$

These measures ensure that are intelligent and do not create random, low-quality solutions. Therefore, a different approach can be adopted by each search agent in the solution area, thereby increasing its searching capacity [26]. To maximize the use of metaheuristics, it is critical to ensure an efficient trade between exploration and extraction. The solution space must be exploited in the first course of iterations; however, we focus more on exploitation in the final iterations. To this effect, the following method is used in SCCSA throughout focus more on experimentation in the first and last iterations [26]:

$$r_1 = a - t\frac{a}{T} \tag{7}$$

where t represents current iterations and T denotes the maximum number of iterations. The flowchart for the SCCSA technique is depicted in Fig. 5. A group of initial solutions produced randomly within the search space of the issue serves as the starting point for SCCSA, just as it does for any other meta-heuristic optimization process. Achieved global best position as optimal solution when algorithm achieves maximum number of iterations.

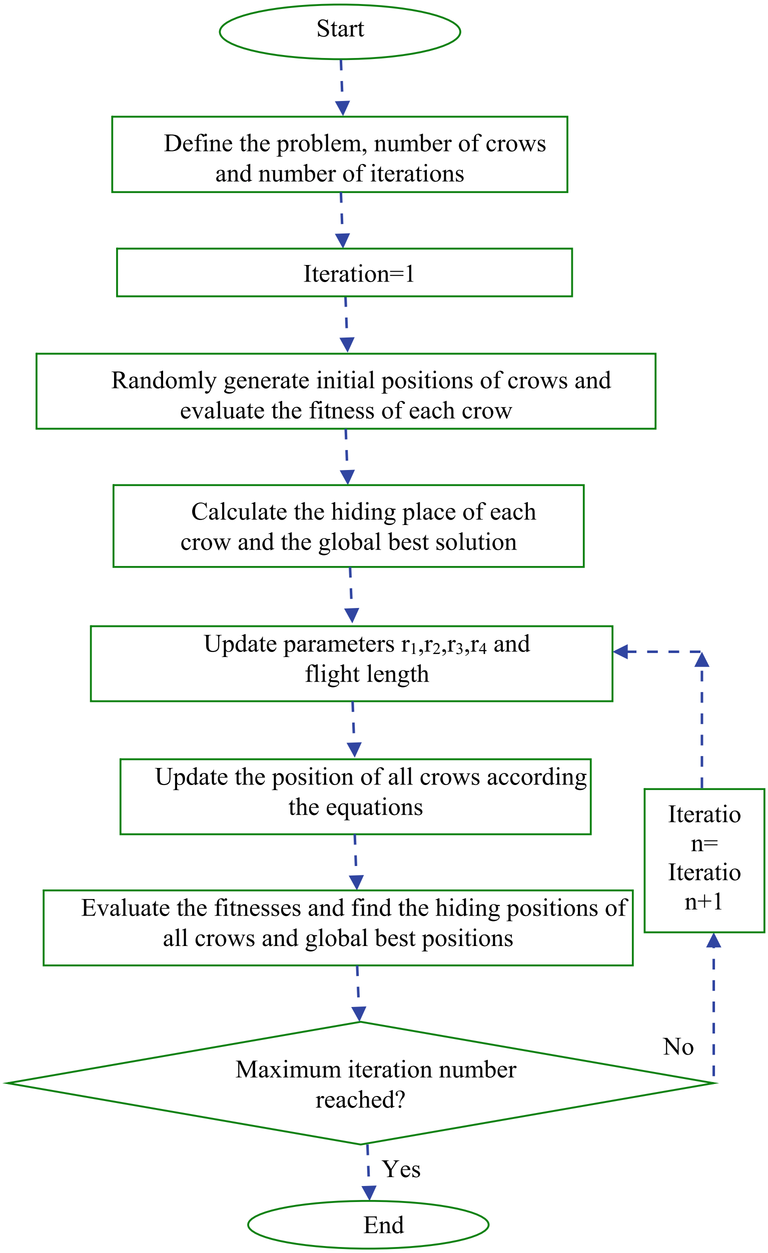


Fig. 5 The flow chart of Hybrid SCCSA algorithm

7 Implementation of Hybrid SCCSA Algorithm in AWJ Process

The goal of this investigation is to identify the most effective combination of AWJ cutting parameters possible for achieving the smallest possible kerf taper angle during machining. The mathematical model produced using response surface methods can be considered of as an objective function constrained by the range of the cutting parameters. The problem was framed as a bounded optimization problem with the goal of minimizing the kerf taper angle.

i.e. Minimize kerf taper angle, with the limits,

200 Mpa $\leq$A $\leq$300 Mpa

600 g/min $\leq$B $\leq$800 g/min

50 mm/min $\leq$C $\leq$150 m/min

1 mm $\leq$D $\leq$3 mm

As a single objective optimization, the SCCSA approach is presented for minimizing kerf taper angle. Matlab 2013a is used to create the Hybrid SCCSA algorithm's computer code. Control parameters are determined through trail runs, and the resulting solutions are close to optimal for the given problem. In general, the SCCSA method should be used in the AWJ process optimization to produce a set of process parameters for the global optimum machining criterion at a reasonable computing cost and in an acceptable amount of time. The SCCSA optimization results demonstrate that the ideal kerftaper angle can be obtained by varying the jet pressure, abrasive mass flow, traverse rate, and stand-off distance. The optimum values of the input process parameters are given as: Jet pressure = 292.406 Mpa, abrasive mass flow rate = 605.838 g/min, traverse rate = 140.62 mm/min and stand-off distance = 2.94136 mm. The convergence profile in Fig. 5 indicates that the minimum kerf taper angle value is 0.5342 degrees. Besides that, the optimal solution obtained for the minimum kerf taper angle is at the 41th iteration of the SCCSA algorithm as indicated on Fig. 5. In addition, the experiment was carried out to ensure that the optimization result was valid. The AWJ machine was programmed with the expected cutting parameters, and the obtained kerf taper angle of the machined composite was 0.5631 degrees, which was very near to the predicted value of 0.5342 degrees. As a result, the SCCSA optimization validity could be validated.

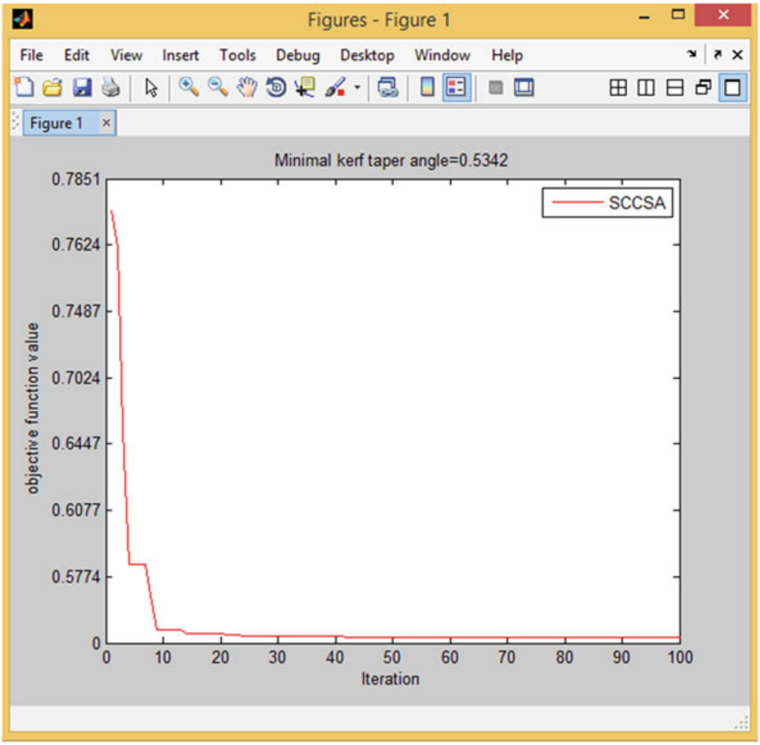


Fig. 6 SCCSA algorithm convergence profile

8 Conclusion

In this paper, the experimental investigation has been performed using RSM based box behnken design to evaluate kerf taper angle in AWJ cutting of pineapple fiber reinforced polymer composites. Then, a Hybrid algorithm has been applied for minimizing the kerf taper angle. The following conclusions are drawn:

- The established second order equation exhibits a strong correlation between predicted and measured values.
- Regression models have demonstrated a high aptitude for modeling and establishing correct fitness functions.
- The hybrid SCCSA algorithm is effectively implemented for obtaining the minimum taper angle of kerf.
- The ideal combination of AWJ machining parameters to achieve the lowest possible kerf taper angle of 0.5342 degrees was found to be 292.406Mpa, 605.838 g/min, 140.62 mm/min and 2.94136 mm for Jet pressure, abrasive mass flow rate, traverse rate and stand-off distance, respectively
- Validation experiments confirm the outcomes acquired after optimization.

References

1. Sathish P, Kesavan R, Vijaya Ramnath B, Vishal C (2015) Effect of fiber orientation and stacking sequence on mechanical and thermal characteristics of banana-kenaf hybrid epoxy composite. SILICON 9:577–585
2. AjitDhanawade SK (2018) Study on carbon epoxy composite surfaces machined by abrasive water jet machining. J Compos Mater 53:2909–2924
3. Ramraji K, Rajkumar K, Dhananchezian M, Sabarinathan P (2020) Key experimental investigations of cutting dimensionality by abrasive water jet machining on basalt fiber /fly ash reinforced polymer composite. Materials Today: Proceedings 22:1351–1359
4. MeltemAltinKaratas HG, MuammerNalbant, (2019) Optimization of machining parameters for abrasive water jet drilling of carbon fiber-reinforced polymer composite material using Taguchi method. Aircr Eng Aerosp Technol 92:128–138
5. Vigneshwaran S, Uthayakumar M, Arumugaprabu V (2017) Abrasive water jet machining of fiber-reinforced composite materials. J Reinf Plast Compos 37:230–237
6. Kale A, Singh SK, Sateesh N, Subbiah R (2020) A review on abrasive water jet machining process and its process parameters. Materials Today: Proceedings 26(2):1032–1036
7. Shukla R, Singh D (2017) Experimentation investigation of abrasive water jet machining parameters using Taguchi and Evolutionary optimization techniques. Swarm Evol Comput 32:167–183
8. Zain AM, Haron H, Sharif S (2011) Optimization of process parameters in the abrasive waterjet machining using integrated SA–GA. Appl Soft Comput 11:5350–5359
9. Chakraborty S, Mitra A (2018) Parametric optimization of abrasive water-jet machining processes using grey wolf optimizer. Mater Manuf Processes 33(13):1–13
10. Jagadeesh B, Dinesh Babu P, Nalla Mohamed M, Marimuthu P (2017) Experimental investigation and optimization of abrasive water jet cutting parameters for the improvement of cut quality in carbon fiber reinforced plastic laminates. J Ind Text 48:178–200
11. Dhakal HN, Ismail SO, Ojo SO, Paggi M, Smith JR (2018) Abrasive water jet drilling of advanced sustainable bio-fiber-reinforced polymer/hybrid composites: a comprehensive analysis of machining-induced damage responses. The International Journal of Advanced Manufacturing Technology 99:2833–2847
12. Shanmugam A, Krishnamurthy K, Mohanraj T (2019) Experimental study of surface roughness and taper angle in abrasive water jet machining of 7075 aluminum composite using response surface methodology. Surf Rev Lett 27(3):1950112
13. Chaturvedi C, Rao P, Khan M (2021) Optimization of process variable in abrasive water jet Machining (AWJM) of Ti-6Al-4V alloy using Taguchi methodology. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2021.05.040
14. Tripathi DR, Vachhani KH, Icon DB, Soni Kumari V, Kumar R, Abhishek K (2021) Experimental investigation and optimization of abrasive waterjet machining parameters for GFRP composites using metaphor-less algorithms. Mater Manuf Processes 36:803–813
15. P. Thamizhvalavan, N. Yuvaraj, S. Arivazhagan (2021). Abrasive Water Jet Machining of Al6063/B4C/ZrSiO4 hybrid composites: a study of machinability and surface characterization analysis, Silicon, 1–29.
16. Tamilarasan A, Rajmohan T, Ashwinkumar KG, Dinesh B, Praveenkumar M, Dinesh Reddy R, Surya Kiran KVV, Elangumaran R, Krishnamoorthi S (2021) Hybrid WCMFO algorithm for the optimization of AWJ process parameters. IOP Conference Series: Materials Science and Engineering 954:1–10
17. Arumuga Prabu V, Thirumalai Kumaran S, Uthayakumar M (2016) Performance evaluation of abrasive water jet machining on banana fiber reinforced polyester composite. Journal of Natural Fibers 14:450–457
18. V. Durga Prasada Rao, M. Mrudula, V. Navya Geethika (2019). Multi-objective optimization of parameters in abrasive water jet machining of carbon-glass fiber-reinforced hybrid composites, Journal of The Institution of Engineers (India): Series D, 100, 55–66.

19. Jeykrishnan J, Vijaya Ramnath B, Sree Vignesh S, Sridharan P, Saravanan B (2019) Optimization of Process Parameters in Abrasive Water Jet Machining/Cutting (AWJM) of Nickel Alloy using Traditional Analysis to Minimize Kerf Taper Angle. Materials Today: Proceedings 16(2):392–397
20. Gupta V, Pandey P, Garg M, Khanna R, Batra N (2014) Minimization of Kerf Taper Angle and Kerf Width Using Taguchi's Method in Abrasive Water Jet Machining of Marble. Procedia Materials Science. 6:140–149
21. Yuvaraj N, Kumar M (2018) Optimisation of abrasive water jet cutting process parameters for AA5083-H32 aluminium alloy using fuzzy TOPSIS method. Int J Mach Mach Mater 20(2):118
22. Abhishek Madankar,ParikshitDumbhare,YogeshVasantraoDeshpande,Atul B. Andhare, Purushottam. S. Barve (2021) Estimation and control of surface quality and traverse speed in abrasive water jet machining of AISI 1030 steel using different work-piece thicknesses by RSM, (online), 1–9.
23. Tamilarasan A, Renugambal A, Manikanta D, Sekhar Reddy GBC, Sravankumar K, Sreekar B, Prasadreddy GV (2018) Application of crow search algorithm for the optimization of abrasive water jet cutting process parameters. IOP conference series: materials science and engineering 390:1–12
24. SeyedaliMirjalili(2016). SCA: A Sine Cosine Algorithm for solving optimization problems, Knowledge-Based Systems,96,120–133.
25. Askarzadeh A (2016) A novel metaheuristic method for solving constrained engineering optimization problems: Crow search algorithm. Comput Struct 169:1–12
26. SoheylKhalilpourazari, Seyed Hamid Reza Pasandideh (2020). Sine–cosine crow search algorithm: theory and applications, 32, 7725–7742.

Bio Fibre Composites: Mechanical Characterization

Studies on Mechanical Characterisation of Bio-Fibre Reinforced Polymer Composites

N. B. Karthik Babu, V. Vignesh, N. Nagaprasad, K. Palanikumar, and A. Pugazhenthi

Abstract Polymer Matrix Composite (PMC) is a potential candidate material for structural, automotive and aerospace applications due to its high strength to weight ratio, non-corrosive and affordable. Because of these reasons, PMC's are widely used as an alternate material for both load bearing and non-load bearing applications. However, synthetic fibre usage in PMC fabrication limits its application in various sectors due to increased environmental awareness like non-degradability, land-filling and so on. This forced research community to develop eco-friendly material associated with equivalent mechanical properties and where bio-fibres are coming to picture here. Recently, an importance of bio-fibre reinforced PMC's have been realised and numerous studies were carried out to study various mechanical properties such as tensile, flexural, hardness and impact properties of bio-fibre reinforced PMC's. In this chapter, the effect of single bio-fibre, hybrid bio-fibre and synergistic effect of filler-fibre combination on mechanical properties are presented and reason/mechanism for properties improvement is analysed. This motivates novice researchers to understand failure mechanisms under mechanically loaded environment and lead to widen the way to carry out further research in bio-fibre composites.

N. B. K. Babu (✉)
Department of Mechanical Engineering, Assam Energy Institute, A Centre of Rajiv Gandhi Institute of Petroleum Technology, Sivasagar, Assam 785697, India
e-mail: kbabu@rgipt.ac.in

V. Vignesh
Department of Mechanical Engineering, Sethu Institute of Technology, Kariapatti, Tamil Nadu 626115, India

N. Nagaprasad
Department of Mechanical Engineering, ULTRA College of Engineering and Technology, Tamil Nadu, Madurai 625 107, India

K. Palanikumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, Chennai 600 044, India

A. Pugazhenthi
Department of Mechanical Engineering, University College of Engineering Dindigul, Tamil Nadu, Dindigul 624622, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_8

Keywords Polymer composites · Bio-fibres · Eco-friendly materials · Mechanical strength · Failure mechanisms

1 Introduction

Testing of any material or composite is essential to predict their strength and withstand-ability against mechanical load. These testing are helpful to avoid catastrophic failure of a material and severe damage too [1]. Under mechanical load, behaviour of a composite material is different when compared to pure metals therefore measurement of various basic mechanical properties of a polymer composite is mandatory. These behavioural differences of polymer composites are majorly due to its anisotropic nature of composites and they are composed of two or more constituents. Therefore, it can be realised that assessment of mechanical properties of any composite material is highly important and based on those test results it can be reveal that whether a proposed composite material is fit for a particular application or not (Fig. 1).

Firstly, it is realised that testing of composite materials is important, and then the following questions would come in to picture. What type of test or load? (Whether it is tensile or compressive or shear, etc.), what would be the test environment? (Whether it is room temperature or elevated temperature), what will be the test parameter? (Whether it may be sudden load or gradual load or long-term load) and so on. The answer for these questions is depends on end use of the proposed composite materials. Hence, it should be screwed-up those properties requisite of a composite material is highly depends on end application i.e. where a composite material is going to use? Based on these a designer can perform design process (of any component used in structural, automotive, aeronautics, and other applications) with the help of tests data.

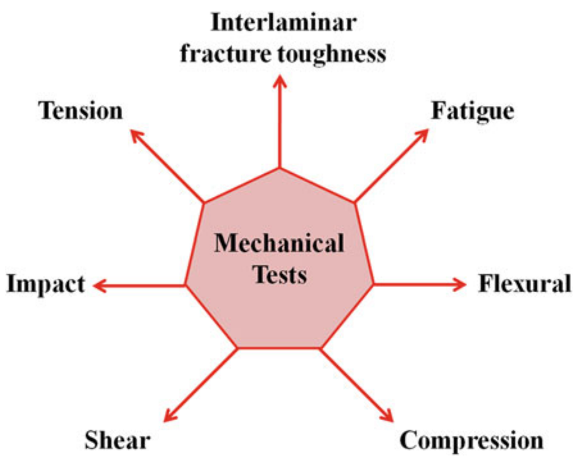


Fig. 1 Most common tests for a composite material

2 Mechanical Characterisation of Composite Materials

2.1 Tensile Test

Tensile properties of a material can be assessed the most common test known as tensile test and this test is simple test where two opposite collinear tensile forces are applied along the longitudinal direction (as shown in Fig. 2). The applied force is gradually increased till specimen fracture and a stress–strain curve is plotted simultaneously during the test. In general, one can able to get following properties from tensile test (i.e.) tensile strength (in MPa), elongation at break (%), poisons ratio, Young's modulus. Among these, the tensile strength is the most fundamental property of a material can be defined as an ability of that material against a force that tends to pull/stretch it. For newly any developed composite material, measurement of tensile properties is essential and outputs of this test are highly useful to predict suitability of a material for selected application. In order to assess the abovementioned properties composite samples should be designed with ASTM standards or any other suitable standards. Most commonly used standard is ASTM D3039 for determining the tensile properties of a polymer matrix composite [2].

During bio-fibre reinforced polymer composites fabrication, a manufacturer must concern about matrix/fibre interface, compatibility between fibre and matrix,

Fig. 2 Tensile test machine and its stress distribution

porosity, distribution of fibre, and so on. The abovementioned parameters have enormous influence on tensile strength and other properties of a composite material (Fig. 2).

2.2 Flexural Test

Flexural properties of a material can be found through 3-point or 4-ponit bending test (also called as flexural test) and the properties obtained such as flexural strength, flexural modulus, elongation, etc. using this test are equally important to disclose flexural strength of a material when a specimen is subjected to bending load. During flexural test, a load is applied normal to the axis of specimen and subjected to bending till the failure of a specimen (as shown in Fig. 3). Like tensile test, a stress–strain curve is plotted simultaneously during the flexural test and aforesaid properties were also recorded. Both tensile and flexural tests are regularly used techniques to assess the fracture strengths of materials (Fig. 3).

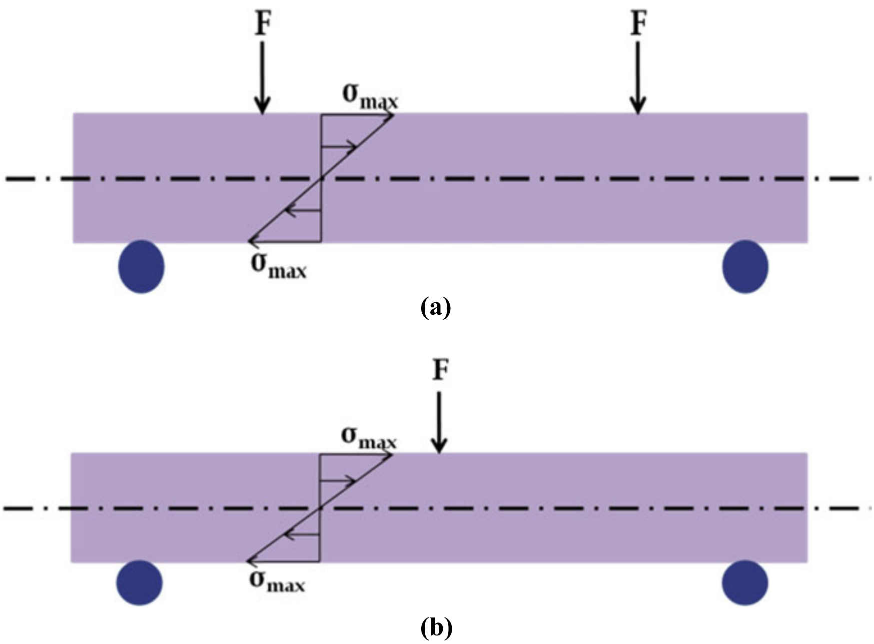


Fig. 3 **a**, **b** schematic of bending tests **a** 3-point and **b** 4-point and their stress distribution (where, F = applied load and σ = stress)

2.3 Impact Test

Before introduction of the carbon fibre reinforcement, a minimum interest was paid on study of impact response of glass fibre reinforced polymer composites (as shown in Fig. 4). However, concern on impact response of a polymer composite material was increased when carbon fibre reinforcement was used as reinforcement in polymers. This was due to the higher brittleness of carbon fibre compared to glass fibre and these glass fibre reinforced polymer composites exhibited better performance under impact load [3]. Since natural fibre reinforced composites are gradually replacing synthetic fibre reinforced polymer composites in structural and automotive applications, impact behaviour of these materials is likely to become increasingly important. The impact resistance of bio-fibre reinforced polymer composites has recently been tested using a variety of test methods. The capacity of a material to withstand a shock/sudden load or an applied stress at high speed is known as impact resistance. Impact strength is asignificant mechanical property of materials that are used for many potential engineering sectors such as automobiles, construction, aeronautics and many more. It is determined by a variety of factors, including strength, stiffness, Young's modulus, fibre span and orientation, and physical bond and compatibility between fibre and matrix, among others. In addition, it also depends on method of test used to assess the impact energy.

Fig. 4 Impact testing machine

2.4 Hardness

Hardness is the significant property of a material this displays the resistance against plastic deformation, typically by indentation. Polymers and their composites are relatively soft materials, and the hardness of these materials is usually determined using a shore hardness tester. Hard plastics are commonly graded on the shore D hardness scale, whereas soft rubbers are graded on the shore A hardness scale. The shore D hardness test is used to determine the hardness of polymer composites in the majority of studies. In general, the output of shore D hardness range between 0 and 100 and the higher value of the polymer indicates that the material's hardness increases. The samples should be cleaned with acetone before being measured, and the testing surface should be smooth. During the test, the sample is mounted on a flat surface, the test probe is pressed against the surface for 15 to 20 s, and the tester's measurement is taken. The test is repeated seven times per sample to improve the reliability of the results, and the average hardness of the samples can be taken into account. The portability, ease of measurement/handling, and reduced measurement time are all advantages of using the shore D hardness test. Figure 5 depicts a typical image of a shore D hardness tester.

Fig. 5 Shore D hardness tester

3 Mechanical Characterisation of Single Fibre Reinforced Polymer Composites

The polymer composites composed of long bio-fibres and polymeric resin could be useful for structural or civil engineering applications and their usage have been steadily increasing in the automotive and construction sectors due to their advantageous features like high specific strength and stiffness. Conversely, performance of various natural fibres reinforced polymer composites has been questioned due to high variability in mechanical properties for structural reliability analysis. The mechanical properties of a polymer composite can be studied through various tests. From those tests, the effect of natural fibre content on stress–strain relationship, ultimate tensile strength, Young's modulus, ductility, and toughness can be determined experimentally [3] (Fig. 6).

Intrinsically most polymers have less strength compared to metals. Hence, fibre reinforcement has become essential to strengthen raw polymers and withstand against mechanical load. In this way the synthetic and natural fibres are gained their importance in polymer composites and widened their use in different sectors. In general, natural fibre shows lower mechanical strength relative to synthetic fibres. Therefore, evaluation of mechanical properties of natural fibresis equally important before manufacturing polymer composites. Reddy et al. analysed the tensile properties of

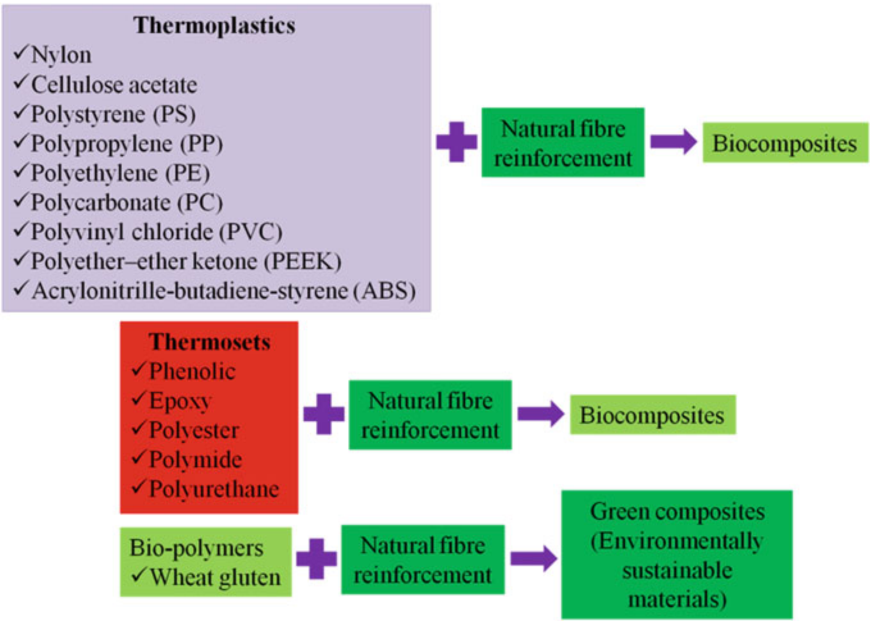


Fig. 6 Different combinations of polymer composites

borassus fine fibres and these properties of the fibres increased after 8 h of alkali treatment due to better fibre structure. Based on enhanced tensile properties, renewability and eco-friendly nature, borassus fine fibres was suggested as reinforcement in manufacturing of green composites [4]. The figure shows different polymer composites which is composed of both biocomposites and green composites. The Fig. 6 discusses natural fibre reinforcement in different category of polymers, in which a biocomposite have anyone compound (either matrix or reinforcement) as biodegradable material however, a term green composite is completely (all components) biodegradable material. The natural fibres reinforcements have significant drawbacks like low mechanical strength, poor thermal stability, low useful life span and soon. Kandola et al. used jute and sisal fibres as reinforcement and fabricated jute/PP, sisal/PP, jute/PLA, and sisal/PLA composites in this PP based composites are partially synthetic and PLA based composites are fully eco-friendly materials. The mechanical strength of prepared composites was assessed through tensile, flexural and impact test. The higher Young's modulus and flexural modulus were recorded in tensile and flexural tests respectively by the PLA-based composites and these values were higher than respective PP-based composites. In addition, sisal fibre reinforced composites exhibited higher Young's modulus and flexural modulus compared to jute fibre reinforced composites [5].

Since 1990s, natural fibre polymer composites have been potentially employed in automotive industries. For instance, major products such as interior door panels, trunks, roofs, seat backboards, dashboards and analogous partsproposed for automotives. Automotive parts made of bio-fibre reinforced polymer composites have been significantly grew-up by ca. 50% from 2000 to 2005. Similarly, in domestic, construction, musical instruments, and packaging materials are the few areas where natural fibre reinforced polymer composites are actively involved [6]. However, some of the typical factors like non-linear behaviour of natural fibre, properties decay over time, etc. are restricting their application in heavy load bearing sectors. In addition, bio-fibres have reduced thermal stability than synthetic glass fibres. Most natural fibres are partially/fully decay around 240 °C. Most importantly composition of natural fibres (cellulose, hemicelluloses, lignin, and extractives) significantly depend on cultivation place like geographic location where the plants are grown up and mechanical properties could vary when there is a change in these composition [7]. However, bio-fibres such as coir, flax, sisal, jute, banana, kenaf, and hemp show the advantages like minimum carbon footprint and biodegradable combined with a good specific strength and stiffness at an affordable cost. Dobah et al. explained the mechanics of jute/polyester composites using tensile and fatigue tests. The uni-axial and multi-axial loads were applied on 25 vol.% of jute fibre reinforced polyester composites and found that the composites showed 42 MPa of tensile strength and 7.5 N-m of torsion strength under uni-axial tensile and torsional loads respectively. On the other hand, these values were reduced to 22 MPa and 5 N-m in multi-axial static tests. Based on the test results, the authors suggested that the use of jute/polyester composite materials in sectors such as car and aircraft interiors could show effective performance with lower weight, cost and carbon footprints [8].Sivakumar et al. investigated randomly palmyra fibre reinforced composites with effect of potassium permanganate chemical treatment. The composite plate fabricated by hand lapup method and the results showed that treated plamyra fibre enhanced superior tensile and flexural properties than the untreated fibre [9]. Karthikeyan et al. studied the natural fibre as banana ribbon with polyester composites with effect fibre rope mat and random orientation. The above composites were fabricated by using compression moulding machine. From this study it has been asserted that by rope mat composites showed maximum mechanical properties that when compared to other composites [10]. Vijaya kumar et al. prepared a new natural fibre as caryota fibre to fabricate the composites plates with help of compression moulding machine. The optimum results were obtained at 40% of fibre content when compared other composites weight percentages and utilized the material in automobile and other related industries [11]. Vignesh etal introduced a new chopped indian mallow fibre with polyester composites and compression moulding technique is adopted for manufacturing the composite plate with different weight percent 10 to 50%. The result indicated that increasing the fibre content in composites plate show the ultimate mechanical and thermal properties of the composites [12]. Palanikumar et al. developed the mechanical and vibrational analysis of bio caryota reinforced polymer composite to decreases the environmental effect and light weight load carrying structures. Compression moulding machine is used for fabricating the composite laminates with varying weight % from 10 to 45%. The bio caryota fibre shows better properties than other natural fibre composites in the literatures [13].The short bio-fibres have been used for semi-structural or non-load bearing parts in the automotive sector where low weight vehicles imply minimum fuel consumption as well as low carbon emissions. However, structural or load bearing parts demand comparatively higher mechanical properties and this could be achieved when using long natural fibres as reinforcement.

4 Mechanical Characterisation of Hybrid Fibre Reinforced Polymer Composites

Versatile ways to improve a material strength is given in Fig. 7. From long year ago, the natural fibres have been reinforced to improve the strength of polymer composites and recognised as successful reinforcement for polymer composites. Over the time, hybrid fibres have been used in polymer composites manufacturing and hybrid fibres exhibited higher mechanical strength compared to single fibre reinforced polymer composites because of synergistic effect of two fibres [14].

Currently, large number of researchers from engineering and science background has been introducing new natural fibres due to increased environmental awareness between researchers. This could be a bright chance to develop and analyse properties of hybrid natural fibre reinforced composites and leads to new material development. In addition, researchers have been motivated towards the development of green composites i.e. fully biodegradable material and there are huge opportunity

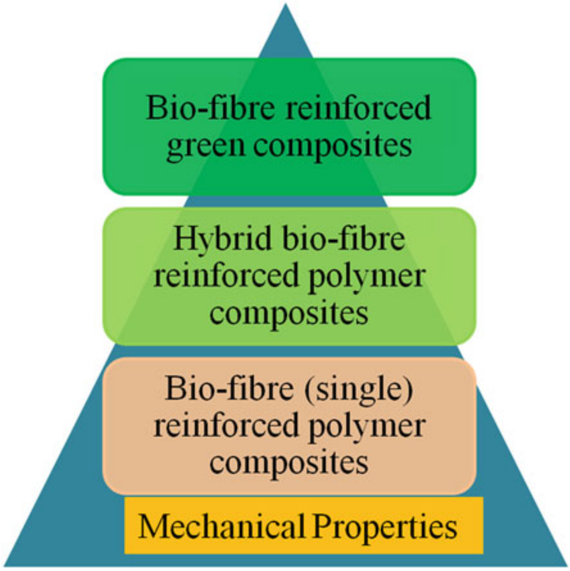


Fig. 7 Evolution of biocomposites

for such green composites development and only countable works have been carried out in this fully biodegradable hybrid composites.

Hybridization two or more fibres can enhance mechanical properties because of (i) the variation in diameter of two fibres is possible in hybridization, this leads to effective settling of fibres within the matrix with increased surface area contact and leads to effective stress transformation [9]. (ii) During mechanical tests, a fibre with low elongation take applied load initially and break first; followed to this applied load is taken by fibre with high elongation which could reduce the sudden failure of matrix and leads to improved stress transfer from matrix to fibres and consequential enhancement of mechanical properties [14]. Many researchers have been reported the synergistic effect of synthetic and natural fibres reinforcement on mechanical properties hybrid fibre reinforced polymer composites and achieved good improvement in mechanical properties. A composite contains hybrid fibres reinforcement balances their properties deficiency by one another fibre(s) during mechanical loading.

Srinivasan et al. prepared hybrid epoxy composites in which the reinforcements used were banana fibre, flax fibre and glass fibre. It was concluded that the hybrid epoxy composite has better mechanical properties compared to single glass fibre reinforced composite (GFRP)when subjected to impact and flexural loads. Also, it is noticed that the hybrid composite exhibited better mechanical strength compared to single fibre composites [15]. In another work, Alavudeen et al. developed banana/polyester, kenaf/polyester and banana/kenaf/polyester composites and analysed their mechanical properties using tensile, flexural and impact tests. Among aforesaid composites, the woven banana/kenaf fibre added hybrid composites showed higher mechanical strength and this was due to hybridization effect of kenaf with banana fibres [16].

Ramesh et al. analyzed the mixing of sisal—jute—glass fibre reinforced polyester composites to find increasing of various applications. The mechanical characteristics of hybrid composites were tested through ASTM standards. Sisal–jute- GFRP fibre composites showed best performance in terms of mechanical properties and morphology studies of fractured specimen provides the internal cracks, internal structures and internal fractured of composites while various mechanical loading[17]. Palani kumar et al. investigated green hybrid polymer composites to evaluate the mechanical properties of the composites. The result indicated better tensile, flexural and impact strength due to hybridization of composites with low pollution effects. The SEM analysis proved the fibre breakage, void and failure of resin packages were found in after testing of composites specimen [18]. Stalin et al. studied the hybrid vetiver fibre matvinyl ester composites to evaluate the tensile, flexural, hardness and impact properties. The composites plate fabricated by compression moulding with various combination at 45° and 90° direction.The hybrid double-layer fibre mat composites indicates ultimate tensile and flexural properties and it is found that vetiver double-layer fibre mat composites at 90° direction, indicating high impact strength than a banana and other hybrid fibre mat composites[19]. Vignesh et al. focused effects of their wood sawdust filler on hybrid and twisted hybrid indian mallow/ roselle fibre composite. The ten combination of hybrid and twisted hybrid plates were fabricated by compression molding machine and composite specimen were tested both warp and weft direction as per ASTM standards. Twisted hybrid double layer composites yarn mat and wood sawdust filler sample recorded significantly greater improvement on the mechanical properties at warp direction, when compared other reported hybrid composite materials. Above composites were recommended to fabricate the automobile and electronics industries applications [20]. Stalin et al. carried out to evaluate the mechanical properties of hybrid Typha angustata mat reinforced vinyl ester composites. The Typha angustata/Banana mat composites exhibited better impact strength and hardness due to the exchange the properties between the two natural fibres and sufarce morphology of fracture specimen such as fibre fracture, matrix fracture, delamination of fibre, fibre bending and fibre pull out were found by SEM analysis [21] (Fig. 7).

In short, the hybrid fibres reinforcement is an effective technique to achieve better mechanical strength. Moreover the growth of scientific techniques and new fibre establishment would allows us to develop new hybrid composites that could be a good alternate for conventional single fibre added composites.

5 Summary

In short the natural fibre reinforcements are gaining their importance in polymer composites development because of its availability, affordability, renewable and importantly low carbon footprint on the environment after useful life.

As natural fibre is used as reinforcement in the manufacturing of polymer composites, mechanical properties such as tensile strength and modulus, flexural strength and modulus, and so on can be effectively altered (or) changed.

The reinforcement of natural fibres in naturally derived polymers together forms a green composite and such composites have been needed to be developed since these green materials are biodegradable in nature and leads to sustainable development. Introduction of new natural fibre opened door to next level research in polymer composites and analyse of mechanical properties. More importantly, hybrid natural fibres reinforcement need more focus since hybrid polymer composites shows superior mechanical properties than to single fibre reinforced composites.

Hybrid surface modified fibre reinforced polymer composites are still more likely to develop and evaluate their effect on mechanical properties of polymer composites. With appropriate chemical treatment, the surface of the natural fibre can be changed.

References

1. N.B. KarthikBabu, T. Ramesh, S. Muthukumaran (2020), Physical, tribological and viscoelastic behavior of machining wear debris powder reinforced epoxy composites, Journal of Cleaner Production, 272, 122786.
2. Bhat R, Mohan N, Sharma S, Pratap A, Keni AP, Sodani D (2019) Mechanical testing and microstructure characterization of glass fiber reinforced isophthalic polyester composites. J Mater Res Technol 8(4):3653–3661
3. Winkel JD, Adams DF (1985) Instrumented Drop Weight Impact Testing of Cross-Ply and Fabric Composites. Composites 16(4):268–278
4. Obi Reddy K, UmaMaheswari C, Mukul Shukla JI, Song AV (2013) Tensile and structural characterization of alkali treated Borassus fruit fine fibers. Compos B Eng 44(1):433–438
5. Kandola BK, Mistika SI, Pornwannachai W, Anand SC (2018) Natural fibre-reinforced thermoplastic composites from woven-nonwoven textile preforms: Mechanical and fire performance study. Compos B Eng 153:456–464
6. Sun Z (2017) Progress in the research and applications of natural fiber-reinforced polymer matrix composites. Sci Eng Compos Mater 25(5):1–12
7. Komuraiah A, Shyam Kumar N, Durga Prasad B (2014) Chemical Composition of Natural Fibers and its Influence on their Mechanical Properties. Mech Compos Mater 50:359–376
8. Dobaha Y, MostefaBourchak AbderrezakBezazi, Belaadi A, Scarpa F (2016) Multi-axial mechanical characterization of jute fiber/polyester composite materials. Compos B Eng 90:450–456
9. S. Sivakumar, V. Vignesh, V, I. Vijay Arasu, G. Venkatesan, G, B. R. M.Rabi, M.A. Khan (2021), Experimental investigation on tensile and flexural properties of randomly oriented treated palmyra fibre reinforced polyester composites, Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2021.01.51.
10. Karthikeyan MKV, Balaji AN, Vignesh V (2016) Effect of rope mat and random orientation on mechanical and thermal properties of banana ribbon-reinforced polyester composites and its application. Int J Polym Anal Charact 21(4):296–304
11. Vijayakumar S, Palanikumar K (2020) Evaluation on mechanical properties of randomly oriented Caryota fiber reinforced polymer composites. J Mater Res Technol 9(4):7915–7925
12. Vignesh V, Balaji AN, Nagaprasad N, Sanjay MR, Khan A, Asiri AM, Siengchin S (2021) Indian mallow fiber reinforced polyester composites: mechanical and thermal properties. J Mater Res Technol 11:274–284

13. Palanikumar K, Subbiah V (2019) Bio caryotafiber reinforced polymer composites: mechanical properties and vibration behavior analysis. J Bionic Eng 16(3):480–491
14. Gupta MK, Srivastava RK (2016) Mechanical Properties of Hybrid Fibers-Reinforced Polymer Composite: A Review. Polym-Plast Technol Eng 55(6):626–642
15. Srinivasan VS, RajendraBoopathy S, Sangeetha D, Vijaya Ramnath B (2014) Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite. Mater Des 60:620–627
16. Alavudeen A, Rajini N, Karthikeyan S, Thiruchitrambalam M, Venkateshwaren N (2015) Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation. Mater Des 66:246–257
17. Ramesh M, Palanikumar K, Reddy KH (2013) Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites. Compos B Eng 48:1–9
18. Palanikumar K, Ramesh M, Hemachandra Reddy K (2016) Experimental investigation on the mechanical properties of green hybrid sisal and glass fiber reinforced polymer composites. Journal of Natural Fibers 13(3):321–331
19. Stalin A, Mothilal S, Vignesh V, Sanjay MR, Siengchin S (2020) Mechanical properties of hybrid vetiver/banana fiber mat reinforced vinyl ester composites. J Ind Text. https://doi.org/10.1177/1528083720938161
20. Vignesh V, Balaji AN, Rabi BRM, Rajini N, Ayrilmis N, Karthikeyan MKV, Al-Lohedan HA (2021) Cellulosic fiber based hybrid composites: A comparative investigation into their structurally influencing mechanical properties. Constr Build Mater 271. https://doi.org/10.1016/j.compositesb.2005.04.001
21. Stalin A, Mothilal S, Vignesh V, Nagarajan KJ, Karthick T (2021) Mechanical Properties of Typha Angustata/Vetiver/Banana Fiber Mat Reinforced Vinyl Ester Hybrid Composites. Journal of Natural Fibers 1–12. https://doi.org/10.1080/15440478.2021.1875366

Fatigue Behaviour of Banyan/Neem Fibers Reinforced with Nano Cellulose Particulated Hybrid Epoxy Composite

T. Raja, P. Anand, and V. Mohanavel

Abstract This research involves developing the composite laminates using natural fibers of neem fiber, bidirectional woven banyan fibers, sawdust cellulose with epoxy matrix varying with reinforcement weight fraction to quantify the fatigue behaviour of epoxy composite. As per the ASTM standard fatigue test was performed with 3 different ratios of hybrid composites are 90/45 g, 67.5/67.5 g, and 45/90 g of banyan and neem fibers. In this study, the life of composite laminates can reveal from fatigue analysis in samples 'A' withstand more cycles of rotation 5979 compared with the other two samples, which indicates when increasing bidirectional banyan is woven mat weight percentage was given the positive influence of variable fatigue load and at the same time short neem fibers are shows less efficient life of hybrid composite. The surface morphological analysis was used to analyze the failure mode during the fatigue test of this composite laminates by scanning electron microscope (SEM) analysis.

Keywords Natural fibers · Neem fiber · Banyan fiber · Fatigue behaviour · Nano cellulose · ASTM standard · Hybrid composite · Polymer matrix

1 Introduction

The natural fibers are pineapple, coir, ramie, flax, sisal, banana fibers, etc. are minimum cost fiber and used as a substitution for synthetic fibers. It makes the development of a hybrid composite with unidirectional, continuous, and 40% v/v

T. Raja (✉) · P. Anand
Department of Mechanical Engineering, Vel Tech Rangarajan Dr, Sakunthala R&D Institute of Science and Technology, Chennai 600062, India

P. Anand
e-mail: dranand@veltech.edu.in

V. Mohanavel
Centre for Materials Engineering and Regenerative Medicine, Bharath Institute of Higher Education and Research, Chennai 600073, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_9

hybrid of banana fibers and sisal fibers (1:1) natural rubber latex, and also it describes the mechanical properties [1]. Developed a natural fiber of neem and banyan with epoxy matrix was given 25 MPa with a maximum amount of bidirectional woven fabric composite and it was 41% more than increasing of chopped neem fiber hybrid composite [2]. The materials introduced from rubber latex are elastomer, and hybrid fibers as reinforcement promoted the mechanical properties are tensile strength, flexural strength and hardness [3]. The rigidity of the developed material also increased when compared to the pure late and also this material can also be applied in the applications of engineering, industrial and commercial [4]. The manufacturing and properties of bidirectional banana/jute mixture fiber fortified composites and contrasts and the single characteristic fiber strengthened composites [5]. The physical properties of the natural fiber composites were acquired by testing the composite for thickness, tensile, flexural, between laminar shear, effect, and hardness properties [6]. Newly introduced fibers like Polyester and nylon acts as a reinforcement in fiberglass for developing hybrid composite. It is a low-density material and very cheap for fabricating parts with better impact and fatigue strength [7]. Due to this extreme property level, these materials are used for fabricating parts for aircraft and automobiles [8]. A method for assessing the impact of porosity flaws on the interlinear tensile (ILT) fatigue behaviour of carbon/epoxy tape composites, which can be employed in fatigue-critical structural designs in aero planes. This work introduced the rotorcraft engineering community to advanced structural methods that could account for manufacturing issues including porosity in composite parts and enable accurate assessment of their capability and useful life [9, 10]. Natural fibers materials are easily available and the manufacturing process of natural fibers is easier than other composites. Hence, the advantages of this natural fiber motivate the researchers to study the possibility of developing reinforced composites and testing the properties of the material for different applications [11]. Reviewed the chemical and mechanical properties of natural fibre reinforced polymer-bonded composites and the processing techniques compared for the reinforced composite materials. The awareness in the environment and the greenhouse result promoted the building, motorized stuffing businesses to look at the ecological resources able to restore the conservative artificial fibres [12]. The usual fibres considered better substitute as in leathery form and obtained since basil greeneries at minimum charges. Because of, there is a strong faith in the natural fibres compared to the natural fibres [13]. The Young's modulus of the natural fibre works based on the ratio of fibre weight. When the fibre weight ratio increased, it also increases and then it is decreased. Various natural fibres consist of higher young's modulus when compared with the glass fibre. The other natural fibres have the lowest young's modulus when compared with the Jute, hemp, flax, pineapple. Thus the chemical and mechanical possessions of usual fibre were reviewed [14].

The fatigue behaviour of basalt fibre reinforced epoxy polymer (BFRP) composites is investigated, as well as the degradation mechanism of BFRP under various cyclic stress levels were analyzed the mechanical properties of kenaf fiber reinforced polymer composite [15]. The composite improves the features of the polymers. Kenaf fiber has excellent tensile and flexural strength. 40% fiber loading is the optimum condition in polymer composites which give better mechanical properties [16]. The extraction of fibres requires less energy. Production costs are kept to a minimum. During extraction, there is no tooling wear and no skin discomfort. Excellent thermal and acoustic insulation. They are long-lasting, environmentally friendly, and biodegradable. The fatigue behaviour of composite materials reinforced with different types of glass fibers is characterized in air and seawater. Seawater aging is shown to reduce fatigue lifetime [17]. Temperature is significantly influenced by fatigue strength, the major negative influence of fatigue life is need on a large quantity of new input of all material, and the constant amplitude fatigue life of fiber-reinforced polymer composites is continuously higher than that of glass fiber reinforced plastic [18]. Reviewed the manufacturing process with the reinforcement fibre particle. Addition manufacturing is a robust paradigm of manufacturing for producing efficient parts with better mechanical property than unreinforced particles. Practically all monetarily accessible AM strategies could profit by different reinforcement of fibre processes. Ongoing advancements in 3D printing strategies for fibre fortified polymers, to be specific, combined testimony displaying (FDM), overlaid object fabricating (LOM), Stereo Lithography (SL), expulsion, and particular laser sintering (SLS) assessed right now comprehend the patterns and future bearings in the individual zones [19]. Notwithstanding additional quality, strands have likewise been utilized in 4D printing to control the difference in shape or to expand after 3D printing, directly out of the printing be [20]. Although AM of fibre/polymer composites is progressively creating and under exceptional consideration, there are a few issues should have been tended to including void development, poor adhesion of strands and framework, blockage because of filler incorporation, expanded curing time, modelling, simulation, and so on. Regardless, various imaginative procedures spotted among ongoing work attempting to conquer these difficulties with new material or manufacturing systems [21]. High throughput robotized methods are these days assuming a key job in polymer composite assembling in various enterprises, for example, car and aviation. There is a need to deliver high volume parts effectively [22]. Supply and demand cycles of neem and banyan fibres robotized fabricating strategies, for example, computerized tape layup and mechanized fibre condition can create composite parts proficiently, and with the approach of added substance producing the intricacy of these segments are expanding [23].

From the above motivation, this present study is related to natural fibers of banyan and neem fibers are reinforced with epoxy matrix to develop a composite laminate for three different samples by conventional hand layup methods and to analyse the fatigue effect of this hybrid composite.

2 Materials and Methods

2.1 Materials Used

Natural fibers are the potential alternate materials for synthetic in numerous applications due to their weight density ratio. In this work, natural fibers of neem fiber in hewed type, banyan fibers are bidirectional woven material type used as prime reinforcement and epoxy polymer with hardliner is used as matrix material by 10:1 ratio and the sawdust cellulose used as filler material and to fabricate with three different samples to changing the weight fractions of reinforcement by conventional hand layup technique is used for the fabrication process of this hybrid composite [24]. Neem fibers and banyan woven fabric were collected from the go green industry, Chennai, India, and the epoxy polymer and sawdust filler were collected from Jayanthi enterprises, Chennai, India. The details about the material extraction is discussed in the following sections.

2.2 Banyan Fiber

Banyan fibres are considered to be one of the easily available material used for the preparation of fibre reinforced composites. The banyan is long lived aerial root plant and possess a fibre source for a very long time in manufacturing [25]. These plants are considered to be a good potential for the reinforcing composite material and the fibres used for the reinforcement can be extracted from the roots. In Fig. 1 shows the banyan tree, fiber form and banyan woven fabric.

2.3 Neem Fibre

Neem tree is a largely available plant in the country with a source of fibre content in the ancient times. It is hugely found on the home and office and it is a fast-growing tree having a height of 15 to 20 m [26]. Though these years, numerous research work has been conducted to experiment the preparation of fibre composite with the fibre extracted from neem tree. The chopped neem fiber is shown in Fig. 2.

2.4 Applications of the Hybrid Epoxy Composite

The far-reaching utilization of NFPCs in epoxy composites because of its less weight, generally good quality, moderately less manufacture charge, corrosion opposition, absolutely recyclable, refining the superficial completion formed share composites,

Fig. 1 Banyan fiber extraction from banyan tree

Fig. 2 Neem fiber extraction from neem tree

reasonably significant mechanical strength, and accessible, sustainable bases when contrasted with artificial fibres. Then again, there is a real disservice of the NFPCs, for example, dampness assimilation, confined handling temperature, and variable quality and this detriment prompted constraining their performance. The following applications have done with neem and banyan fibers reinforced epoxy composite are floods, typhoons, seismic tremors and in storage gadgets are post-boxes, grain stockpiling storehouses, bio-gas compartments. Also, using this composite laminate can develop the natural fiber composite helmet, car dash panel and car bumper for micro level automotive vehicles.

2.5 Fibre Treatment

Generally, the natural fibres are hydrophilic and having the polar groups in their structure. These natural fibres are consist of several elementary fibres combined with cellulose, hemicellulose, pectin, lignin, etc. For removing the excess elements from these fibres chemical treatments are employed. Past research works proves that the interfacial bonding can be enhanced by the modifying the surface finish of the fibre through alkaline treatment which results in improving its mechanical and thermal properties [27]. In that scenario, this research work, the natural fibre are chemically treated by alkaline for the thermoplastic and thermoset plastic reinforcement. With the hydrogen bonds in the network structure, it can increase the surface roughness and fibre strength. It also modifies the natural fibre by the NaOH from hydroxyl group to alkoxide group respectively.

2.6 Fibre Properties

Before the fabrication process, the collected fibre is analyzed with the natural properties for reinforcement. The property change of the fibre material will reduce the mechanical properties and there by a suitable chemical treatment process is followed in the fabrication to improve the properties of the material at the desired level.

Table 1 reveals the properties of the fibre extracted from the neem and banyan fibre. The property is measured individually for each fibre before it gets reinforced. The fibre is extracted from parent material and measure the properties for any further modification.

Table 1 General Properties of Neem and Banyan Fibre [12]

Properties	Neem Fibre	Banyan Fibre
Group	Natural Fibre	Natural Fibre
Type	Short Fibre	Bidirectional Woven Fabre
GSM	150	100
Fibre diameter	20 micron (average)	20 micron (average)
Density	1.67 g/cc	1.52 g/cc

Table 2 General Properties of Epoxy Bisphenol-F LY556 resin [30]

Feature (graphic)	Strong runny
Solidity at 25 °C	1.3 g/cc
Viscosity at 25 °C	11–13 Pa.s
Temperature for curing	75 °C
Glass Conversion Temperature	135 °C

Table 3 Properties of Araldite HY 951 Hardener [30]

Flash Point	110 °C
Mix Ratio	100:10
Specific Gravity	0.98 g/cm3 at 25 °C

2.7 Matrix Preparation

Epoxy resin is a word acquired by chemical starting point. Epoxy have less subatomic weight. The shade of epoxy is dark colored (or) golden shading. This epoxy resin is having high mechanical properties and furthermore expanded significant equal of electrical protection and great concoction obstruction [28]. Epoxy resin are likewise consuming recital properties like biocompatibility, eco-friendly and fire resistance. Epoxy resin are glue and thirsty in some temperature from 41 to 302°F, they additionally shrivel throughout relieving process. This is utilized to keep from interior loads and furthermore keeps from synthetic substances. This can be utilized in paint initiatives as it dries rapidly and gives self-protective layers, development of automobile, air craft, boats, assembling of different molds and cast, overlays, malleable tooling. Hardener is utilized to build the holding limit of resin. Epoxy resin are not wealthy in holding limit thus to expand the bonding limit hardener is utilized [29]. The epoxy resin properties is given in Table 2.

Hardener HY951 used as a catalyst for bonding purpose and woven glass fiber, carbon fiber & natural fiber used as lamination sheets. This material is mixed with epoxy resin for coating or encapsulating electronic components which work at low voltages. In Table 3, shows the hardner properties used in this matrix.

2.8 Fillers

Fillers decrease the expense of composites, yet in addition, every now and again impart performance upgrades that may not, in any case, be accomplished by strengthening and resin elements alone. Plasters are frequently indicated as extenders, in contrast with resins and fortifications, fillers materials are the most economical of significant ingredients. Filler materials can recover mechanical behavior including fire and smoke recital by diminishing natural substance in composite concealments [31]. Thus, filled resin psychiatrists not exactly unfilled resin, along these lines refining the dimensional control of formed parts. Significant behavior, including water opposition, enduring, surface flatness, firmness, dimensional solidness and temperature obstruction, these are able to be improved through best possible utilization of filler materials. The utilization of inorganic fillers in composites is expanding. At the point when utilized in composite covers, mineral filler materials can represent 40 to 65% by weight. There are various inorganic fillers that can be utilized including with composites materials.

2.9 Fabrication Process

Initially, the fibres are wetted fully with sawdust blended epoxy and stacking the fibre mixture to the required stacking sequence. A thin non-reactive laminate is used to cover the steel board to attain a decent superficial surface. Once complete the process, a mould discharging manager is functional for sticking with epoxy matrix to the surface. The matrix material is applied as layers using a skirmish and the short neem fibre is located on the harden board. Fabrication of neem/banyan fibers hybrid composite was done by traditional hand layup technique, this method is suitable for three different types of materials are used such as short neem fiber, banyan woven fiber, nano particles of saw dust cellulose, and clear liquid of epoxy polymer matrix. Therefore, the hand layup method is selected for fabricating this hybrid composite laminates with variable three different weight ratio of laminates, then to enumerate the fatigue effect of the epoxy composite.

In this fabrication process, initially 30 × 30 cm^2steel box is selected for making the composite laminates and liquid wax is applied thoroughly on steel mold for composite releasing without any external damage during and after the fabrication process. Then the matrix material is applying over the neem and banyan fibers are placed as the second layer over the first layer of neem fiber. The process is frequent for fabricating remaining specimens and this wetted composite laminate is allowed to cure at the temperature of 80 °C on the hot oven for 4 h at a moderate rate of heating 6° C/min, trailed by the after-curative procedure at the treating temperature of 110 °C for 2 h. [32].

After curing the composite laminates are removed from steel mould and they can be selected for further fatigue testing with standard dimensions as followed for this hybrid composite the fabrication process by hand layup method as shown in Fig. 3. The weight fractions of the epoxy composite are given in Table 4.

2.10 Testing of the Hybrid Composite

After complete, the fabrication process of the hybrid composite laminates is conducted to fatigue test for analysis of the efficient life and endurance limit of this natural composite material. As per the ASTM standard E606, the dimension

Fig. 3 Fabrication process of epoxy composite

Table 4 The weight ratio of epoxy composite

Sample	Filler in gram	Epoxy matrix weight in gram	Banyan fiber in gram	Neem fiber in gram	The weight fraction of Banyan/Neem fibers in %	Composite laminate weight in gram
A	25	385	90	45	2:1	545
B	25	385	67.5	67.5	1:1	545
C	25	385	45	90	1:2	545

selected for this fatigue test is $119 \times 13 \times 5$ mm^3 was prepared from each sample of hybrid composite. During the fatigue experiments, samples are experiencing the frequency of 3 Hz for polymer composite material [17]. Fatigue testing is undergone of the hybrid composites as shown in Fig. 4, when the material inclines to a cyclic load with stress level below the tensile and compressive strength is applied. It is a mechanism to evaluate the damage due to the steady deterioration of the composite with increased loads cycles leads to a decrease of load-bearing capacity [18]. The testing parameters of frequency 3 Hz with three tensile properties for the A, B, and C samples are 25, 23, and 20.8 MPa as given in Table 5.

A scanning electron microscope (SEM) is an electron microscope as shown in Fig. 5, which scans a sample with a centered beam of electrons to create images of it. In SEM analysis, the morphologic characterization of the composite laminates superficial is detected. The composite samples are washed properly, air dried, and treated with a 100-layer platinum ion coater, which is observed using a scanning electron microscope at a voltage of 20 kV. Until the micrographs are drawn, a thin layer of platinum is vacuum evaporated onto the composite specimens to increase conductivity [5]. This test can analyse the fracture surface morphology of composite specimens. Prior to SEM findings, both specimens were sputtered with a 10 nm sheet of gold. Using double-sided electrical conduction carbon adhesive tabs, each

Fig. 4 Fatigue testing of hybrid composite

Table 5 Process parameters in fatigue testing

S. No	Specimen description	Load test parameters	Test results
A	Area – 65.000 mm^2 Thickness- 6.50 mm Elastic Modulus- 2.7 GPA Poisson's Ratio- 0.25	Frequency-3.00 Hz Tensile- 25 MPA	Load stable cycle-359 Load half cycle-3000 Last load cycle-5979
B	Area – 65.000 mm^2 Thickness- 6.50 mm Elastic Modulus- 2.3 GPA Poisson's Ratio- 0.25	Frequency-3.00 Hz Tensile- 23 MPA	Load stable cycle-0 Load half cycle-80 Last load cycle-169
C	Area – 65.000 mm^2 Thickness- 6.50 mm Elastic Modulus- 2.1 GPA Poisson's Ratio- 0.25	Frequency-3.00 Hz Tensile- 20.8 MPA	Load stable cycle-0 Load half cycle-40 Last load cycle-80

Fig. 5 SEM microscope

specimen was placed on the microscope's aluminium holder. 5–15 kV was used as an accelerating voltage [7].

3 Results and Discussion

3.1 Fatigue Analysis of Hybrid Composite

The materials can withstand high energy during static loading conditions and at the same time to identify the stress-induced endurance limit of this hybrid composite during cyclic loading can give a positive influence when increasing with bidirectional woven fabric compared with chopped neem fiber composite laminates. The experiments are carryout with three specimens with numerous dimensionality levels are tested and the samples of composites are shown in Fig. 6.

The load cycles during the testing of composites are measures for half, stable and last loads [10]. The results from the testing show that sample 'A' score higher while the other two samples scores lower level respectively. The different level of loading condition shows with a different stress, strain, and elastic modulus range is given in Table 6.

A similar study was developed by glass fiber composite with two different mediums are air and ocean water and to evaluate the cyclic loading capacity for potential materials, in this compared with ocean water the air medium was given more cyclic loading of 1200 cycles/min [3].

Fig. 6 Fatigue tested specimen of the hybrid composite

In this work, the banyan woven fabric and chopped neem fibers are capable to fabricate a composite laminate with three different weight fractions and enumerate the fatigue consequence of this hybrid composite and the graph between load with cycles rotation as shown in Fig. 7 and sample A was given the positive influence of hybrid composite when compared with other samples, its reveals clearly when increasing the banyan fiber loading was given 5979 cycles of the last loading and 3000 cycles of half-cycle loading and its content more cyclic loading capacity compared with increasing of chopped neem fiber. The major impact during this experiment the load distribution from one point to another point in sample A is proper and less stress concentration factor obtained in this sample due to the continuous fibers with woven fabric and at the same time more stress concentration arises in sample C due to more amount of chopped neem fibers was given 80 cycles for last loading and 40 cycles for half cycle loading capacity of this hybrid composite. In the sample, B contains a 1:1 ratio of banyan and neem fibers was given 169 cycles for the last loading condition and 80 cycles for half cycle loading capacity. Therefore, among all the three samples in sample A is 98% more cycles withstand for full and half loading condition compared with sample C and 97% higher than sample B and compared the samples between B and C, 53% more cycles in sample B for full loading and 50% more cycles for half loading condition of the hybrid epoxy composite.

In another study, a composite made of sisal fiber and jute fiber reinforced hybrid polymer composite has analyzed to fatigue behaviour and the outcome shows the better fatigue capacity with increasing of jute woven fabric of 4850 cycles with that loading of 10KN [11] and this hybrid composite is 18% lower fatigue compared with this neem/banyan fibers hybrid composite. The graph between stress and strain is shown in Fig. 8, and this graph revealed in sample A-induced stress of 17.13 N/mm2

Table 6 Parametric analysis of fatigue in hybrid composite specimen

Parameter	Samples					
	A		B		C	
	Test Cycles					
	Half loading	Last loading	Half loading	Last loading	Half loading	Last loading
Peak Stress (MPa)	18.7	18.2	12.72	12.71	11.95	11.81
Stress Valley (MPa)	8.7	8.5	5.16	5.10	4.46	4.37
Stress Range (MPa)	10.0	9.6	7.55	7.60	7.49	7.43
Calculated Peak Strain mm/mm	342.8	339.5	287.51	291.54	272.15	273.25
Calculated Strain Valley mm/mm	178.04	177.2	134.62	138.85	111.898	111.77
Calculated Strain Range mm/mm	164.78	162.2	152.88	152.68	160.25	161.47
Unloading Modulus Load Control (MPa)	0.051	0.058	0.0483	0.0425	0.045	0.039
Loading Modulus Load Control (MPa)	0.0409	0.059	0.0384	0.044	0.0386	0.0486

and the other samples are B and C follows 18.35 N/mm2 and 21 N/mm2, the corresponding strain values are also evaluated for samples A, B, and C are followed 0.007, 0.006 and 0.01 respectively.

3.2 *Surface Morphology of Hybrid Composite*

The finding from the Scanning Electron Microscopy (SEM) micrographs is apparent from the figures that the fibre pull-outs, cracks and loss are the dominant cause of hybrid fibre failure when subjected to tensile loading. These failures are mostly caused by a weak interface between matrix orientations, which contributes to stress accumulation and severe hybrid composite breakdown. The outcome of the Scanning Electron Microscopy (SEM) micrographs is shown in Fig. 9. When hybrid fibres are exposed to tensile compression, fibre pull-outs, breaks, and failure modes

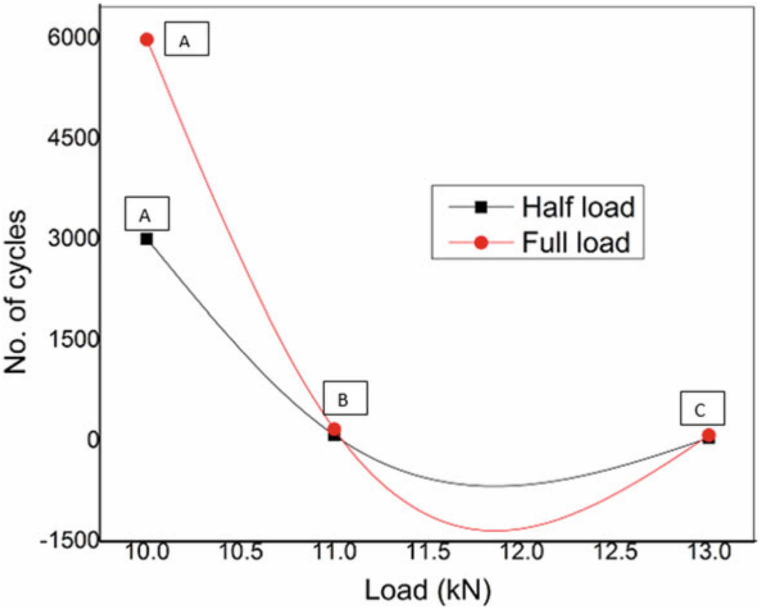


Fig. 7 The graph between load versus number of cycles of hybrid composite

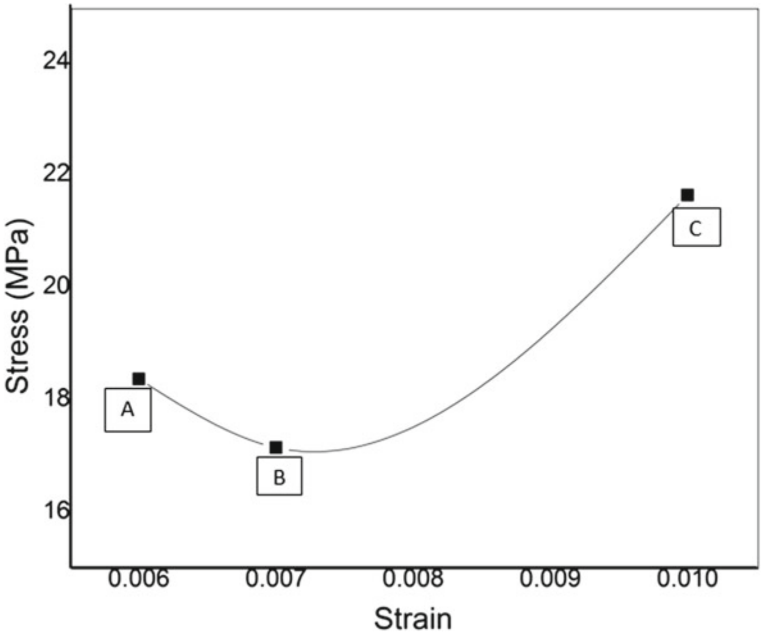


Fig. 8 The stress vs strain of hybrid composite

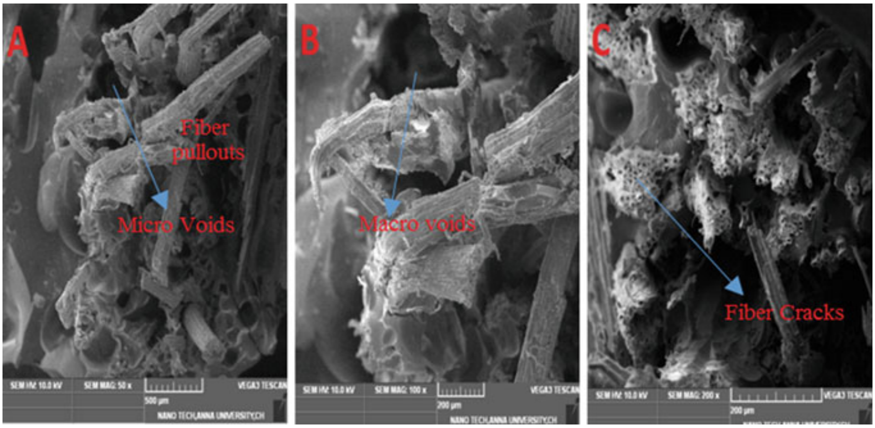


Fig. 9 SEM image of hybrid composite

are the most common causes of failure [9]. These failures are primarily caused by a deprived boundary between matrix orientations, which causes tension accumulation and extreme breakdown of the hybrid composite material [10]. Due to the unvarying degree of stress delivery, using an established weight ratio of banyan fibre in production of hybrid composites results in fewer matrix cracks. a more complicated number of cracks is obtained.

4 Conclusion

The fiber reinforcements consist of short neem fiber and bidirectional banyan woven fabric are loaded in three different sequences and evaluate the fatigue behavior of this hybrid composite. The weight ratio of these two processed hybrid fibers are speckled and evaluates the endurance strength limit and life through Fatigue testing. There are lots of natural fibre reinforced composites but researches on the fatigue analysis of banyan and neem fibre are not so familiar. The fatigue analysis of this polymer composite is very rare. The major findings from the fatigue results of neem and banyan fibers hybrid composite are identified and the efficient fiber natural fibers, fiber ratio are evaluated and the followings points are the major outcomes from this fatigue behavior of hybrid composite. In sample A contains a 2:1 ratio of banyan and neem fibers with effective fatigue outcome compared with the other two samples, this sample can withstand the maximum of 5979 cycles with 10 KN load. It can show the positive impact of hybrid composite and the same time when changing the fiber ratio of 1:2 of banyan and neem fibers was given negative influence for fatigue behaviour of this hybrid composite. The stress-induced maximum of 21.62 MPa in sample C and 18.35 MPa in sample B and the strain rate also is more compared with sample A and it follows the less strain effect in sample A is 0.007 and it is more in sample

C is 0.01. Therefore, from the results of fatigue behaviour for this hybrid composite is suitable with higher cycles of sample A weight ratio of neem and banyan fibers composite can select a potential alternate for synthetic fiber composite.

References

1. Yashas Gowda TG, Sanjay MR, Subrahmanya Bhat K, Madhu P, Senthamaraikannan P, Yogesha B (2018) Duc Pham Polymer matrix-natural fiber composites: An overview. Cogent Engineering 5(1):1–16
2. Ramesh M, Palanikumar K, Reddy KH (2013) Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites. Compos B Eng 48:1–9
3. Yorseng K, Sanjay MR, Tengsuthiwat J, Pulikkalparambil H, Parameswaranpillai J, Siengchin S, Moure MM (2019) Information in United States Patents on works related to Natural Fibers. Current Materials Science 12(4):750–764
4. Bunsell AR, Hemp, jute, banana, kenaf, ramie, sisal fibers (2018), Handbook of Properties of Textile and Technical Fibres, 300–325.
5. Romanzini D, Lavoratti A, Ornaghi HL, Amico SC, Zattera AJ (2013) Influence of fiber content on the mechanical and dynamic mechanical properties of glass/ramie polymer composites. Mater Des 47:9–15
6. Chee SS, Jawaid M, Sultan MTH (2017) Thermal Stability and Dynamic Mechanical Properties of Kenaf/Bamboo Fibre Reinforced Epoxy Composites. Bio Resources 12(7):118–132
7. Asim M, Paridah MT, Saba N, Jawaid M, Alothman OY, Nasir M (2018) Thermal, physical properties and flammability of silane treated kenaf/pineapple leaf fibres phenolic hybrid composites. Compos Struct 20(2):1330–1338
8. Jawaid M, Abdul Khalil HPS, Alattas OS (2012) woven hybrid bio composites: Dynamic mechanical and thermal properties. Compos Part A Appl Sci Manuf 43:288–293
9. Ramesh M, Atreya TS, Aswin US, Eashwar H, Deepa C (2014) Processing and mechanical property evaluation of banana fiber reinforced polymer composites. Procedia Engineering 97:563–572
10. Ramesh M, Palanikumar K, Hemachandra Reddy K (2017) Plant fibre based bio-composites: Sustainable and renewable green materials. Renew Sustain Energy Rev 79:558–584
11. Raja T, Anand P (2019) Evaluation of Thermal Stability and Thermal Properties of Neem/Banyan Reinforced Hybrid Polymer Composite. Materials Performance and Characterisation 8(1):481–490
12. Thandavamoorthy R, Palanivel A (2020) Testing and Evaluation of Tensile and Impact Strength of Neem/Banyan Fiber-Reinforced Hybrid Composite. J Test Eval 48(1):647–655
13. Balaji R, Sasikumar M, Elayaperumal A (2015) Thermal, Thermo oxidative and Ablative behavior of cenosphere filled ceramic/phenolic composites. Polym Degrad Stab 8:150–167
14. Ashworth S, Rongong J, Wilson P, Meredith J (2016) Mechanical and Damping Properties of Resin Transfer Moulded Jute-Carbon Hybrid Composites. Compos B Eng 105:60–66
15. Latha PS, Rao MV, Kumar VK, Raghavendra G, Ojha S, Inala R (2016) Evaluation of mechanical and tribological properties of bamboo–glass hybrid fiber reinforced polymer composite. J Ind Text 46:3–18
16. Swolfs Y, Gorbatikh L, Verpoest I (2014) Fibre hybridization in polymer composites: a review. Compos Part A Appl Sci Manuf 67:181–200
17. KN Bharath, MR Sanjay, Mohammad Jawaid, Harisha, S Basavarajappa , Suchart Siengchin (2019), Effect of stacking sequence on properties of coconut leaf sheath/jute/E-glass reinforced phenol formaldehyde hybrid composites, journal of industrial textiles, 49(1), 3–32.
18. Ganapathy T, Sathiskumar R, Sanjay MR, Senthamaraikannan P, Saravanakumar SS, Parameswaranpillai J, Siengchin S (2019) Effect of Graphene Powder on Banyan Aerial Root Fibers Reinforced Epoxy Composites. Journal of Natural Fibers 12(2):1–8

19. Mr S, Siengchin S, Parameswaranpillai J, Jawaid M, Pruncu CI, Khan A (2018) A Comprehensive Review of Techniques for Natural Fibers as Reinforcement in Composites: Preparation. Processing and Characterization, Carbohydrate Polymers 6(3):11–83
20. Abhishek S, Sanjay MR, George R, Siengchin S, Parameswaranpillai J, Pruncu CI (2018) Development of new hybrid Phoenix, pusilla/ carbon/fish bone filler reinforced polymer composites. Journal of the Chinese Advanced Materials Society 6(4):553–560
21. Salman SD, Leman Z, Sultan MTH, Ishak MR, Cardona F (2015) The effects of orientation on the mechanical and morphological properties of woven kenaf-reinforced poly vinyl butyral film. Bio Resources 11:1176–1188
22. Mahboob Z, El Sawi I, Zdero R, Fawaz Z, Bougherara H (2017) Tensile and compressive damaged response in Flax fibre reinforced epoxy composites. Compos A Appl Sci Manuf 92:118–133
23. Xiang Z, Liu D, H ling Bu, L Deng, H Liu, P Yuan, Peixin D, H Song, (2017) XRD-based quantitative analysis of clay minerals using reference intensity ratios, mineral intensity factors. Rietveld, and full pattern summation methods: A critical review, Solid Earth Sciences 21(4):1–14
24. Jawaid M, Khalil HA (2011) Effect of layering pattern on the dynamic mechanical properties and thermal degradation of oil palm-jute fibers reinforced epoxy hybrid composite. BioResources 6:2309–2322
25. Huo S, Thapa A, Ulven CA (2013) Effect of surface treatments on interfacial properties of flax fiber-reinforced composites. Adv Compos Mater 22(2):109–121
26. Hristozov D, Wroblewski L, Sadeghian P (2016) Long-term tensile properties of natural fibre-reinforced polymer composites: comparison of flax and glass fibres. Compos B Eng 95:82–95
27. Mohd.Farhan Zafar, M. Arif Siddiqui, (2020) Preparation and characterization of natural fiber filled polystyrene composite using in situ polymerisation technique. Advances in Materials and Processing Technologies. https://doi.org/10.1080/2374068X.2020.1798087
28. Raja T, Anand P, Karthik M, Sundaraj M (2017) Evaluation of Mechanical Properties of Natural Fiber Reinforced Composites – A Review. International Journal of Mechanical Engineering and Technology 8(7):915–924
29. Brito C, de Carvalho Bello, Antonella Cecchi, (2017) Experiments on natural fibers: durability and mechanical properties. Advances in Materials and Processing Technologies 3(4):632–639
30. Zafar MF, Arif Siddiqui M (2020) Effect of filler loading and size on the mechanical and morphological behaviour of natural fibre-reinforced polystyrene composites. Advances in Materials and Processing Technologies. https://doi.org/10.1080/2374068X.2020.1793261
31. Raghavendra Subramanya DN, Reddy S, Sathyanarayana PS (2020) Tensile, impact and fracture toughness properties of banana fibre-reinforced polymer composites. Advances in Materials and Processing Technologies 6(4):661–668
32. Balaji R, Sasikumar M, Elayaperumal A (2015) Thermal, Thermo oxidative and Ablative behavior of cenosphere filled ceramic/phenolic composites. Polym Degrad Stab 8:1021–1038

Mechanical Characterization of Kenaf/Carbon Fiber Reinforced Polymer Matrix Composites with Different Stacking Sequence

K. Karthik, C. Rathinasuriyan, T. Raja, and R. Sankar

Abstract The primary aim of this research is to look into the mechanical properties of hybrid composites materials. Hybrid composite laminates made different reinforcements have found use in the automotive industry and aerospace industries. These laminates incorporated the significant of the reinforcements used in constructions. Hybrid composite laminates comprising carbon fiber and kenaf bio fiber with changing stacking sequences over the hand layup process. Epoxy resin (LY556) and hardener (HY951) are present in the matrix material with a mixed ratio of 10:1. Four different hybrid laminates were produced with five order kenaf and of carbon in different stacking sequences. The arranged laminates were cut according to ASTM and exposed to mechanical properties. Fractured surfaces of the sample microstructure were analyzed.

Keywords Carbon fiber · Kenaf fiber · Hybrid polymer matrix composite · Mechanical properties · Scanning Electron Microscope (SEM)

1 Introduction

Composite materials have lightweight and height strength. Hybrid composites are more advanced composites as compared to FRP composites. Multiple reinforcing phases and a single matrix phase are all possible in hybrids. When related to other

K. Karthik (✉) · C. Rathinasuriyan · T. Raja
Department of Mechanical Engineering, Vel Tech Rangarajan Dr, Sagunthala R&D Institute of Science and Technology, Avadi, Chennai 600062, India
e-mail: karthikk@veltech.edu.in

C. Rathinasuriyan
e-mail: rathinasuriyanc@veltech.edu.in

T. Raja
e-mail: rajat@veltech.edu.in

R. Sankar
Department of Mechanical Engineering, SRM University, Haryana, Delhi, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_10

fibre reinforced composites, they are more flexible. Usually, a high modulus fibre is mixed with a low modulus of reinforcements. It provides stiffness and low bearing qualities, while the low modulus fibre has more damage resistant and lowers the material cost.

Changing the volume ratio and stacking sequence of different plies can changes possessions of a hybrid materials [1–3]. Heavy metal, ceramic, or polymer may be the reinforcement material and the matrix material, it provides reinforcement stiffness [4–6]. When efficiently produced, the new collective material looks extra remarkable than would be the case if each material were produced separately. The structural properties of composites have been studied in aerospace industries applications [7].

Medical instruments need for the production of composite with both a polymer and metal matrix are more straightforward. Thermosets and thermoplastics are two commonly used polymer types, which is exact crossways a wide range of polymer environments, implying the filling element is self-determining of matric improper.[8–10].

The tensile strength outcomes presented the finest strength and the modulus was in carbon way surveyed by Kenaf fiber [11, 12]. Studied the carbon fiber reinforced Hybrid Matrix Composite designed to improve the properties of traditional material damping. Carbon fiber reinforced with epoxy polymeric compounds interface reaction. It is still curing epoxy-based process with a strongly cross-related morphology and slightly cross-related and healing elastomer of polyurethane. The study of the hybridized interfacial matrix's carbon fiber and chemical reactions related to phase reactions and flexible material damping after epoxy migration are discussed [13].

The experimental analysis has shown that they are in good agreement [14]. Because of their enhanced properties, hybrid laminate materials containing natural fibres are becoming more popular in a variety of applications, including building materials, partition walls, and sporting materials. Natural fibre hybrid laminates have found use in a variety of fields, including automotive parts [15, 16]. The significance of adding kenaf fiber as intermediate material in carbon fiber. It has a huge amount of potential as a substitute synthetic fibres like glass fiber [17, 18].

Mechanical properties of hybrid laminate materials concerning stacking sequence. The reinforcement materials were carbon and kenaf fibers, with the binding material being a mixture of reinforcement.

2 Reinforcements and Fabrication Methods

2.1 Development of the Hybrid Composites

M/s S M Composites, Chennai, Tamil Nadu, India, supplied the carbon and kenaf fibres. As shown in Fig. 1.

(a) Kenaf fibers (b) Carbon fibers (c) Epoxy

Fig. 1 Materials used for fabricating hybrid composite materials. **a** Kenaf fibers **b** Carbon fibers **c** Epoxy

Fig. 2 Fabrication of hybrid composite laminates

Table 1 Properties of reinforcements

Properties	Carbon	Kenaf	Epoxy
q (g/cm3)	1.65	1.4	1.15
Longitudinal strength	3800	223–948	83
E (GPa)	240	53–56	35
% Elongation	1.6	1.4	4.2
Thickness (gsm)	300	190	–
Wave Type	Woven	Woven	-–

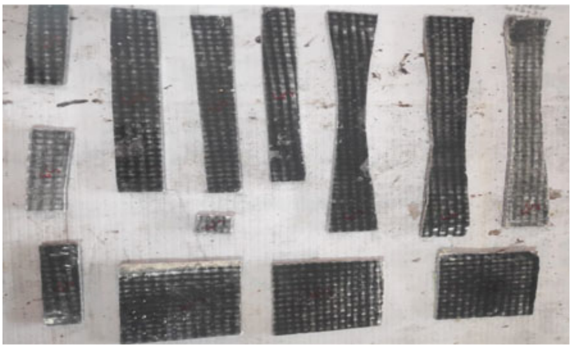


Fig. 3 Specimen cut for mechanical test

Table 2 Composite samples and calculations

Properties	Carbon	Kenaf	Epoxy
q (g/cm3)	1.65	1.4	1.15
Longitudinal strength	3800	223–948	83
E (GPa)	240	53–56	35
% Elongation	1.6	1.4	4.2
Thickness (gsm)	300	190	–
Wave Type	Woven	Woven	--

The current study uses the hand layup method to create a hybrid laminate made up of natural with synthetic fibers in different stacking sequences. The matrix material was made by mixing epoxy and hardener is 10:1 ratio.

Example of single fiber composite laminate produced by below Eq. (1)

$$V_f = \left[\rho_f.W_f/\rho_m.W_f + W_m\right] \quad (1)$$

Where since hybrid fibers are used Eq. (2) was changed as

$$V_f = \frac{\left[\left(\frac{W_c}{\rho_c}\right) + \left(\frac{W_k}{\rho_k}\right)\right]}{\left[\left(\frac{W_c}{\rho_c}\right) + \left(\frac{W_k}{\rho_k}\right) + \left(\frac{W_m}{\rho_m}\right)\right]} \quad (2)$$

3 Experimentation of Hybrid Laminates

3.1 Tensile Test

The specimen for test (tensile) is made from hybrid composites that have been produced.As shown in Fig. 4, the sample was cut according to ASTM D638 standards. Each specimen was fixed between the jaws of the UTM and the tensile load was applied. The readings obtained during the test were recorded.

3.2 Flexural Test

The ASTM D790 standard was used to prepare the hybrid polymer matrix composite specimen for flexural analysis, as shown in Fig. 5. Six samples, having different compositions of reinforcement materials. The prepared specimen was placed over the clamp of FIE UTM, as shown in Fig. 6 The three-point load was applied to the

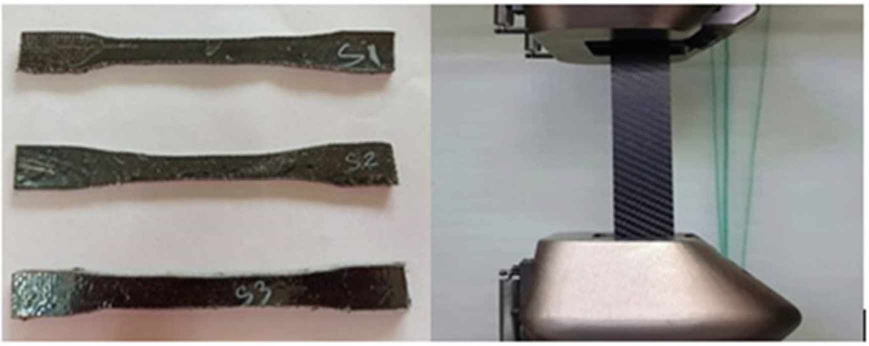


Fig. 4 UTM performing the tensile test

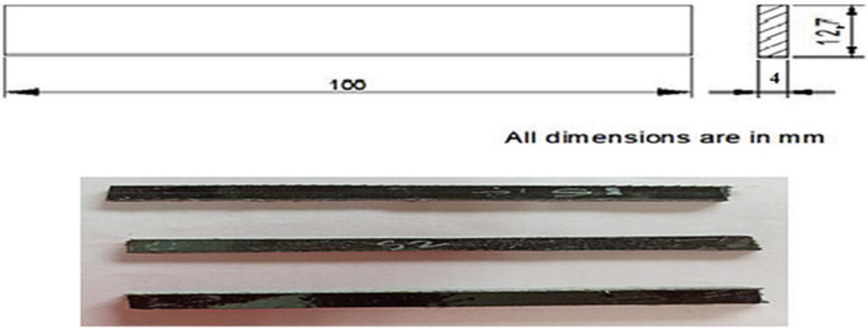


Fig. 5 ASTM D790 standard dimension for flexural test

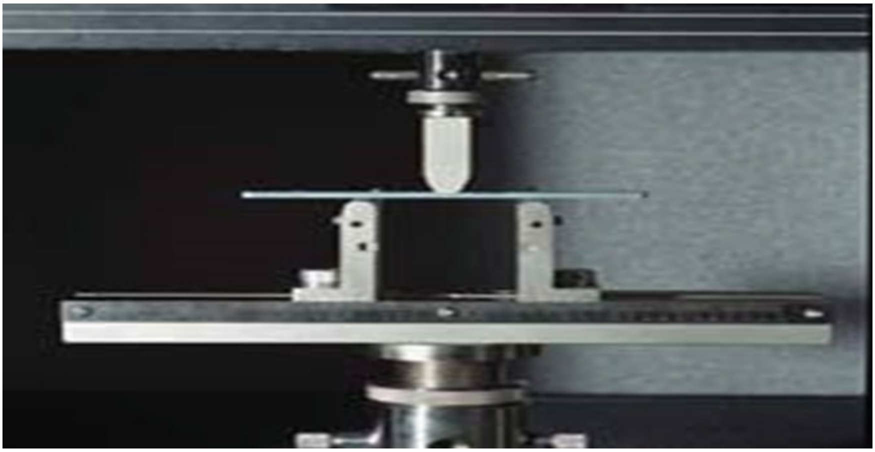


Fig. 6 UTM performing the flexural test

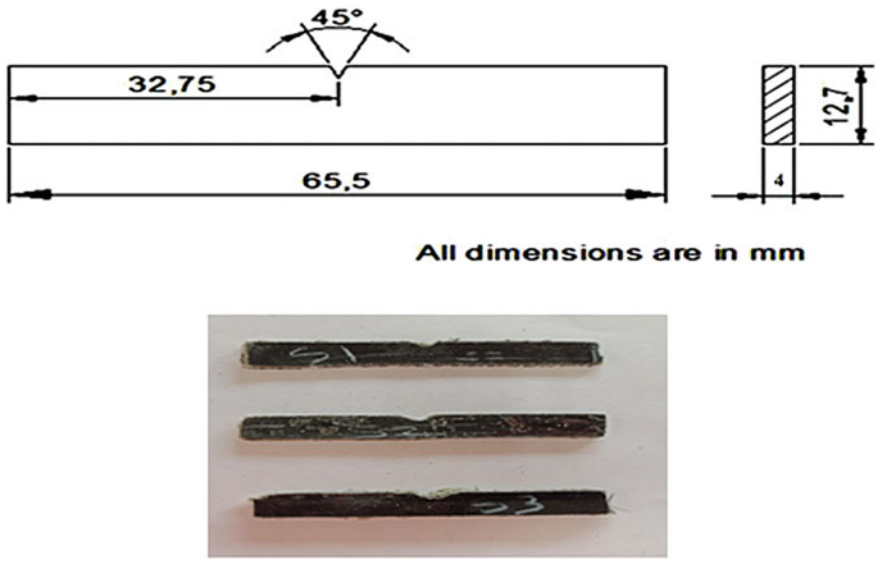


Fig. 7 Specimens cut forcharpy test

sample gradually till the specimen gets fractured. The load applied wasrecorded as the flexural load for the individual model.

3.3 Low Impact Test

The specimen for performing the impact test was cut as per the standards. Along one of the linear edges, A 45° V notch with a depth of 2 mm was cut. As shown in Figs. 7 and 8, the specimen was clamped horizontally to the anvil and facing away from the test machine's hammer. To transmit the required impact load, a 20 kg deadweight hammer was used.

The Charpy impact test V-notch teststandardized high strain-rate and how much energy material absorbs during a fracture.This absorbed energy is a notch strength and stiffness measurement that can be used to investigate sudden shock dependent ductile–brittle nature. This test more used in the companies.

3.4 Hardness Test

The method is used to determine how much resin cured in reinforced thermosetting resins. Figure 9. shows the barcol hardness testing machine.

Fig. 8 Charpy testing machine

Fig. 9 Hardness test as per ASTM E 2240-05 standard and hardness testing machine

The penetration depth of a conical indent was used to determine the indentation resistance of elastomeric soft plastic materials. The hardness of rubber materials was measured with a Shore A durometer, while composites are measured with a Shore D durometer.

4 Analysis and Discussion

4.1 Tensile Behavior of Composite Laminates

Hybrid laminatesare shown in Fig. 10. Because carbon fibres were present in all five layers, the S6 laminate had the highest strength of 250 MPa of all the laminates. The tensile strength of the composite made with all layers of carbon fibres was 20 MPa.

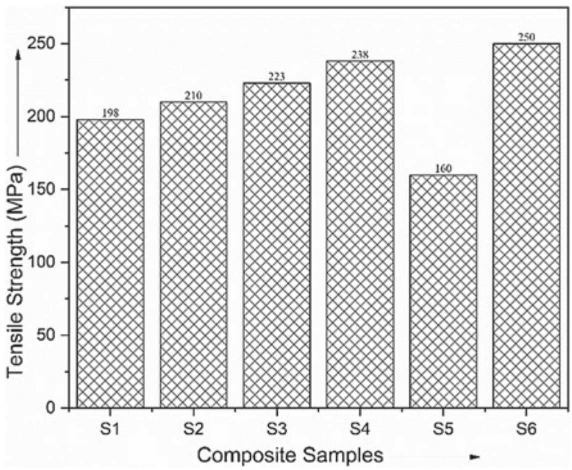


Fig. 10 Tensile properties of hybrid composites

S2, S3, and S4 were the top three hybrid laminate contenders, with tensile strengths of 45.89 percent, 56.17 percent, and 67.24 percent lower than S6.

The tensile strength of these laminates was lower, closer to S5.Carbon fibres have a higher wettability than other materials, allowing the epoxy resin to disperse more easily through voids fibre layers. Proper epoxy resin bonding improved the laminate materials' ability to transfer stress. This demonstrates that natural fibres can joined epoxy resin and change its properties.Sathyaseelan (2020) found that the tensile properties of pure kenaf fibre is more than the tensile strength of hybrid composite.

4.2 Flexural Properties of Hybrid Composite

Figure 11 depicts the flexural strength of the differentlaminates from base composites. The S6 laminate, which contained all five layers of carbon fibres, had the highest flexural strength, measuring 87 MPa.

Their flexural strength improves as the composites are reinforced with high-strength carbon fibre. When specimens with carbon fibre outer layer material flexural strengthare compared to specimens with kenaf fibre as the skin material, it can be seen that specimens with carbon fibre as the skin material have a higher flexural strength. Raja et al. discovered a similar result (2016).

4.3 Impact Properties of Hybrid Composites

This test results of laminates, adherence laminates, and reference laminate S5, which had all the five sequences of kenaf fibres, had the minimum impact strength of 15 J.

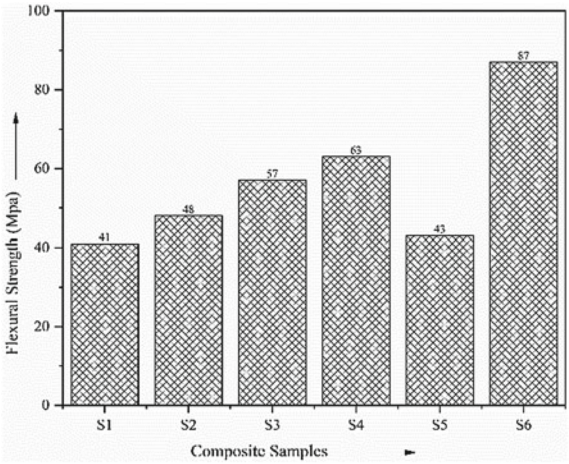


Fig. 11 Flexural properties of hybrid composites

This proves that kenaf, a natural fibre, can change its behavior by reacting with the joining material.

However, the presence of kenaf fibres has the potential to change the properties of the laminates produced. This suggests that the carbon fibres' properties were suppressed by the kenaf fibres acting as cladding.

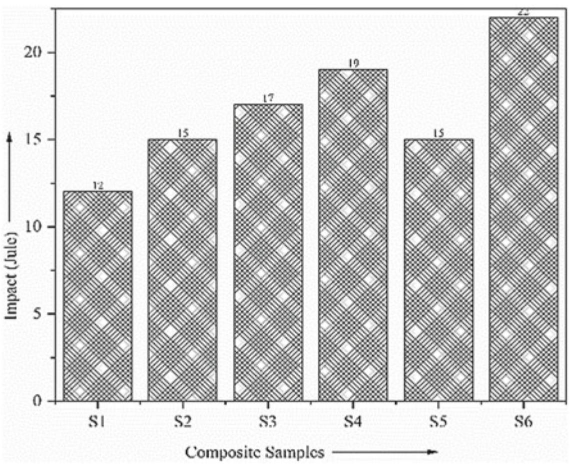


Fig. 12 Impact behaviour of hybrid composites

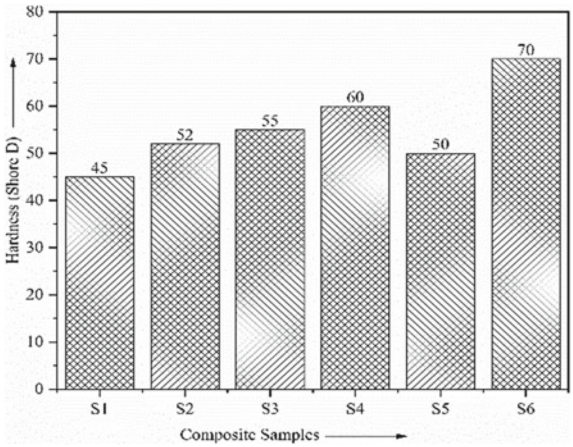


Fig. 13 Hardness properties of hybrid composites

4.4 Hardness Properties of Hybrid Composites

Figure 13 shows the hardness values of the hybrid composite the reference laminates. The base laminate S5, which had all five layers of carbon fibres, had the highest strength.

Values of 70 of D scale. Compared to S3, laminates S5 with all five kenaf layers had a 20% lower hardness value. The S1, S3, and S6 hybrid laminates with kenaf fibres as external layers competed with the S5 hybrid laminate's hardness. The laminates S2 and S4 with kenaf fibres in the outer layer, on the other hand, competed with S6.

4.5 SEM Analysis of Hybrid Composites

The crack appeared due to voids in the matrix and poor adhesion between the matrix and the fibre. As a result, load changed intermediate the fibre sequences was poor.

The experiment fracturereason a matrix failure, fibre pull-out, and fibre breakage in the tensile-tested specimen. Similarly, when the hybrid laminate S4 is compressed, it fails due to kinking of the reinforcements, as shown in Fig. 14 that the fact matrix had crumbled under theforce, the fibres remained intact.

However, the hybrid fibers improved mechanical properties because the tissues lost their hygroscopic property in an epoxy matrix. According to the SEM image, the microspores were also a major contributor to the breakage while applying load. In the case of the hybrid composite with an epoxy matrix, the fibres was found to be intact.

Figure 14 SEM image of the defects occurred at the composite surface during the hand-layup method. There were noticeable defects like blow holes, wormholes, and improper adhesive settings found in the microstructure. This may occur due to a

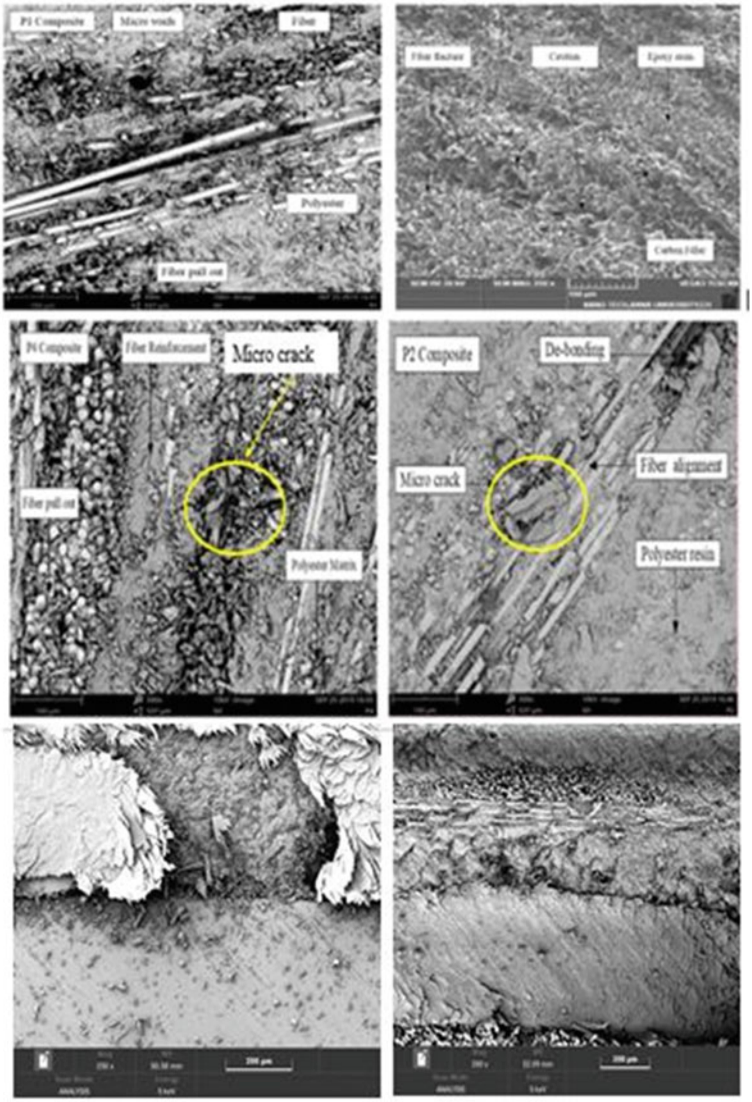


Fig. 14 SEM image of after fractured composite specimens

wrong ratio of mixing matrix materials with the addition of fillers and binders. The blowholes happened when the air was trapped between the layers of the reinforcement and mainly when the binder was poured suddenly without al-lowing the air to escape.

5 Conclusions

The impact of various stacking sequences of mechanical behaviorand microstructural studies of the carbon – kenaf fibrehybrid polymer compositeisinvestigated in this study. Reveled morphological of the fracture zone used SEM images.

1. The hybrid laminate with carbon fibre of outermost layer and kenaf fibre as the middle layer has more tension strength of 238 MPa and bending strength of 63 MPa, among the hybrid laminates. This is due to better kenaf fibre adhesion to the matrix material.
2. Compared to its counterparts, the hybrid laminate with carbon fibre outer layers and kenaf fibre core absorbed maximum impact energy of 20 J. Carbon fibre in the stacking sequence CCKCC was used in hybrid composites to achieve this result.
3. Hardness testing revealed that when compared to reference laminate S4, all hybrid laminates with carbon fibres as top layers have the same hardness value. Hybrid laminates with kenaf fibres as outer layers, on the other hand, had a lower hardness but were able to compete with S6.

Based on the study, this work suggests using CCKCC fibers reinforced polymer composite in high strength structural applications.

References

1. Venkateshwaran N, Elayaperumal A, Sathiya GK (2012) Prediction of tensile properties of hybrid-natural fiber composites. Compos Part B Eng 43(2):793–796
2. Karthik K, Rajamani D, Manimaran A, Udaya Prakash J (2020) Wear behavior of hybrid polymer matrix composites using Taguchi technique. Mater. Today Proc. 33:3186–3190
3. Karthik K, Rajamani D, Manimaran A, Udayaprakash J (2021) Evaluation of tensile properties on Glass/Carbon/Kevlar fiber reinforced hybrid composites. Mater. Today Proc. 39:1655–1660
4. Manickam C, Kumar J, Athijayamani A, Karthik K (2015) Modeling and Multiresponse Optimization of the Mechanical Properties of Roselle Fiber-Reinforced Vinyl Ester Composite. Polym. - Plast. Technol. Eng. 54(16):1694–1703
5. P. Sathyaseelan, P. Sellamuthu, L. Palanimuthu (2020),Influence of Stacking Sequence on Mechanical Properties of Areca-kenaf Fiber-Reinforced Polymer Hybrid Composite,J. Nat. Fibers, DOI: https://doi.org/10.1080/15440478.2020.1745118
6. Arun Prakash VR, Jayaseelan V, Mothilal T, Manoj Kumar S, Depoures MV, Jayabalakrishnan D, Ramesh G (2020) Effect of Silicon Coupling Grafted Ferric Oxide and E-Glass Fibre in Thermal Stability. Wear and Tensile Fatigue Behaviour of Epoxy Hybrid Composite, Silicon 12(11):2533–2544
7. Karthik K, Senthilkumar P (2015) Tribological Characteristics of carbon-epoxy with ceramic particles composites for centrifugal pump bearing application. Int J ChemTech Res 8(6):612–620
8. Venkatasudhahar M, Kishorekumar P, Dilip Raja N (2020) Influence of stacking sequence and fiber treatment on mechanical properties of carbon-jute-banana reinforced epoxy hybrid composites. Int J Polym Anal Charact 25(4):238–251

9. K. Karthik, A. Manimaran, Karunakaran, S. Boominathan, N. Prakash (2018),Forced vibration and dynamic characteristic of hybrid polymer matrix composites, Int. J. Mech. Prod. Eng. Res. Dev.,180–186
10. Karthik K, Manimaran A (2020) Wear behavior of ceramic particle reinforced hybrid polymer matrix composites. Int J Ambient Energy 41(14):1608–1612
11. Senthil Kumar PS, Karthik K, Raja T (2015) Vibration damping characteristics of hybrid polymer matrix composite. Int. J. Mech. Mechatronics Eng. 15(1):42–47
12. Karthik K, Manimaran A, Veerendra Rayudu J, Sharma D (2017) Optimization of the process parameter in the drilling of GFRP using HSS drill. Int. J. Mech. Prod. Eng. Res. Dev. 7(6):403–408
13. Karthik K, Manimaran A, Ramesh Kumar R, Udaya Prakash J (2020) Solar energy performance analysis of basin-type solar still under the effect of vacuum pressure. Int J Ambient Energy 41(8):922–926
14. Vijayakumar S, Palanikumar K (2020) Evaluation on mechanical properties of randomly oriented Caryota fiber reinforced polymer composites. J. Mater. Res. Technol. 9(4):7915–7925
15. K. Palani Kumar, A. Shadrach Jeya Sekaran, L. Dinesh, D. Hari Prasad, K. Deepak kumar (2021),Natural sisal fiber-based woven glass hybrid polymer composites for mono leaf spring: Experimental and numerical analysis," Prog. Rubber, Plast. Recycl. Technol., 37(1),32–48
16. T. N. Valarmathi, K. Palanikumar, S. Sekar, B. Latha, Investigation of the effect of process parameters on surface roughness in drilling of particleboard composite panels using adaptive neuro fuzzy inference system, Mater. Manuf. Process., 35(4),469–477
17. Venkateshwaran N, ElayaPerumal A, Alavudeen A, Thiruchitrambalam M (2011) Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. Mater Des 32(7):4017–4021
18. Palanikumar K, Latha B, Senthilkumar VS, Davim JP (2012) Analysis on drilling of glass fiber-reinforced polymer (GFRP) composites using grey relational analysis. Mater Manuf Process 27(3):297–305
19. Thandavamoorthy R, Palanivel A (2020) Testing and evaluation of tensile and impact strength of neem/Banyan fiber-reinforced hybrid composite". J Test Eval 48(1):647–655
20. Raja T, Anand P, Karthik M, Sundaraj M (2017) Evaluation of mechanical properties of natural fibre reinforced composites - A review. Int. J. Mech. Eng. Technol. 8(7):915–924
21. Raja T, Anand P, Sundarraj M, Karthick M, Kannappan A (2018) Failure Analysis of Natural Fibre Reinforced Pol Y Mer Composite Leaf Spring. Int. J. Mech. Eng. Technol. 9(2):686–689
22. T. Raja, P. Anand (2020), Mechanical investigations on Neem/Banyan fibers reinforced with ceramic powder particulates hybrid polymer composite helmet, IOP Conf. Ser. Mater. Sci. Eng., 988 (1), doi: https://doi.org/10.1088/1757-899X/988/1/012090.
23. Raja T, Anand P (2019) Evaluation of thermal stability and thermal properties of neem/banyan reinforced hybrid polymer composite. Mater. Perform. Charact. 8(1):481–490

Analysis of Mechanical Properties of Jute Fiber Reinforced with Epoxy/Styrene-Ethylene-Butylene-Styrene/Al Composites

T. N. Valarmathi, S. Ravichandran, S. Robin, V. Revanth, R. Siva, S. Sekar, and K. Palanikumar

Abstract Natural fibers are widely used in composite fabrication as they are cheap, safe to manufacture, recyclable, bio-degradable and eco-friendly. In this study, three types of composite panels such as woven Jute fiber and epoxy (JE), woven Jute fiber and styrene-ethylene-butylene- styrene (SEBS) with epoxy (JES) and woven Jute fiber and epoxy with Al metal powder (JEA) are fabricated using hand layup method to investigate the improvement in their mechanical properties. The mechanical proper-ties of three kinds are compared for their effectiveness in enhancing the mechanical properties. It is revealed that the addition of SEBS/Al improves the tensile, flexural, impact strength of the composites.

Keywords Mechanical properties · Woven jute fiber · Epoxy · SEBS · Aluminium · Composites

T. N. Valarmathi (✉) · R. Siva
School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai 600 119, India

S. Ravichandran
Department of Physics, Sathyabama Institute of Science and Technology, Chennai 600 119, India

S. Robin · V. Revanth
Department of Mechanical & Production Engineering, Sathyabama Institute of Science and Technology, Chennai 600 119, India

S. Sekar
Department of Mechanical Engineering, Rajalakshmi Engineering College, Chennai 602107, India

K. Palanikumar
Department of Mechanical Engineering, Sri Sairam Institute of Technology, Chennai 600044, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_11

1 Introduction

Natural fiber composites are becoming trendy as they are very cheap and available plenty, light weight, etc. properties even though the preparation time is more. Many research works which are performed proves the ample usage of natural fiber composites. Nowadays, natural fibres are used in place of glass fibre, due to their advantages [1]. The use of wood in furniture making can be reduced by replacing natural composites like jute fiber composites [3]. The addition of polyester in jute with epoxy composite reduces the processing time and improvement in flexural and tensile properties [1]. The use of natural fiber composites in automobile industries is increased. Increase in weight percentage of jute fiber composite with polypropylene improves the mechanical properties [5]. The low cost and light weight properties of Jute fabric epoxy composite layers, replaces the use of aramid fabric layer [5]. Addition of Al metal powder in hybrid composite panel improves the mechanical properties [4]. The machining parameters affect the natural fiber MDF wood composite panels [6–9]. Various articles on modelling and optimisation of composite panels is reviewed [14]. The tensile strength and elasticity modulus values are moderate for jute reinforcement and Jute/PP commingled composite [11]. The length of jute fiber in polystyrene based composites improves the mechanical properties [4]. Orthophthalic polyester resin with eucalyptus fibers such as granis and urophylla composites with varying fiber concentrations were analysed for the effect on physical and mechanical properties [12].

In this study, three types of composite panels are made using hand layup process using epoxy resin and resin (LY556) and hardener (HY951) such as woven Jute fiber—epoxy described as JE, woven Jute fiber-Epoxy-SEBS described as JES and woven Jute fiber-Epoxy-Al metal powder described as JEA to investigate their mechanical properties and compared.

2 Experimental Procedure

2.1 Materials and Their Properties

Jute is a natural fiber belongs to bast fiber category. Jute is an environmental friendly fiber material because it is biodegradable and also recyclable. Its tensile strength is high. Initially it is mostly used in textile industries and nowadays used in automobile and composite manufacturing applications. Epoxy resins have excellent mechanical properties, heat and chemical resistance, cheap, durable and shrink-age after curing is less. It is biodegradable and environmental friendly. Styrene-ethylene-butylene-styrene (SEBS) behaves as rubber be-cause it is a type of thermoplastic elastomers. The processing of SEBS is easy and it is a strong and flexible material. As it is produced from styrene–butadiene–styrene-copolymer (SBS), its thermal stability is high. Heat, weathering, ultraviolet and oil resistance properties are also high.

Fig. 1 Materials used for fabricating the natural fiber reinforced composites

Aluminium metal powder is light in weight, recyclable, biodegradable ductile, high thermal and electric conductive and corrosion resistive material. Because of the above said properties it founds applications in automobile industries, paint making and as a filler material in polymers as it is act as a stress reducing agent. As all the selected materials are biodegradable, recyclable and environment friendly, the fabricated composites are the best alternate to synthetic fiber composite products. The materials used for fabricating the composites are presented in Fig. 1.

2.2 Composite Preparation

Three types of composites are fabricated. Composite specimens are fabricated using woven jute fiber laminates, epoxy resin, SEBS, Al metal powder and hardener by using hand layup method. The ratio of jute to epoxy is maintained as 1:3. In the first type (JE), the epoxy resin (LY556) is mixed with hardener (HY951). The ratio of epoxy and hardener is maintained as 10:1. In the next type (JES), the epoxy resin and SEBS dissolved in Toluene are mixed with hardener. The ratio of epoxy and hardener is 10:1 and the ratio of epoxy and SEBS is maintained as 10:1. In the third type (JEA), the epoxy resin and Al powder are mixed with hardener. The ratio of epoxy and hardener is 10:1 and the ratio of epoxy and Al powder is maintained as 10:1. Then the mixer is applied on the jute fiber laminates and allowed for curing. The preparation of natural composite panels is presented in Figs. 2 and 3 respectively. The fabricated JE, JES and JEA composite panels are presented in Fig. 4.

3 Specimen Preparation and Testing of Mechanical Properties

The JE, JES and JEA composite specimens are prepared as per ASTM standards. Tests were carried out in MET MECH LAB at Chennai.

Fig. 2 Jute fiber with epoxy resin (JE) composite panel

Fig. 3 Jute fiber with epoxy resin and Al powder (JEA) composite panel

3.1 Tensile Test

The test specimens are prepared using water jet abrasive machine according to ASTM D 638 standard. Water jet abrasive machine is shown in Fig. 5. The UTM and the specimens before and after tensile testing are shown in Fig. 6.

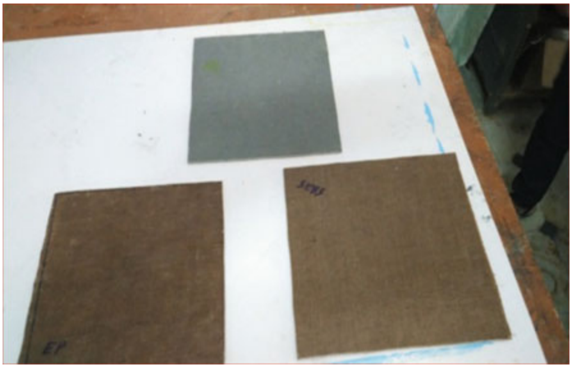


Fig. 4 Fabricated JE, JES and JEA composite panel

Fig. 5 Water jet abrasive machine

3.2 *Flexural Test*

The test specimens are prepared according to ASTM D790 for the flexural test. Flexural test machine and specimens before and after testing are shown in Fig. 7.

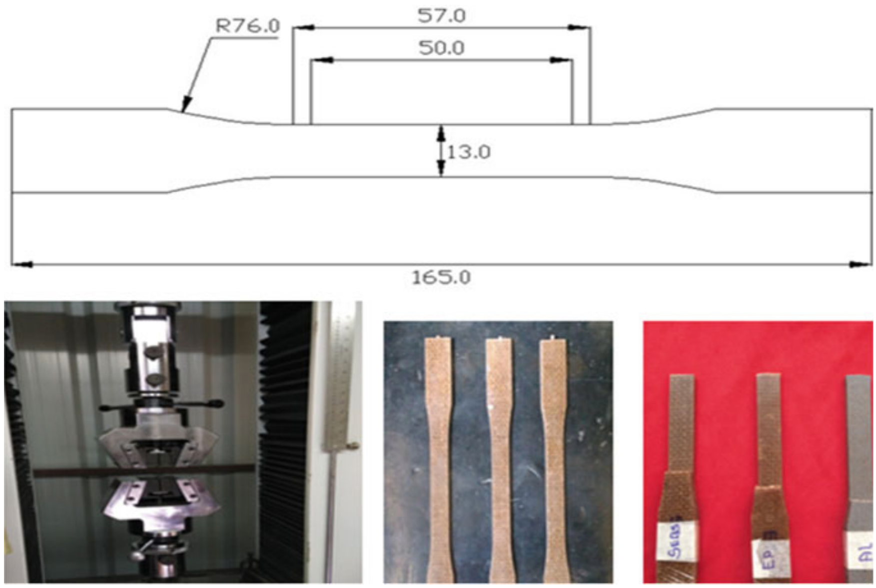


Fig. 6 UTM and specimens before and after tensile test

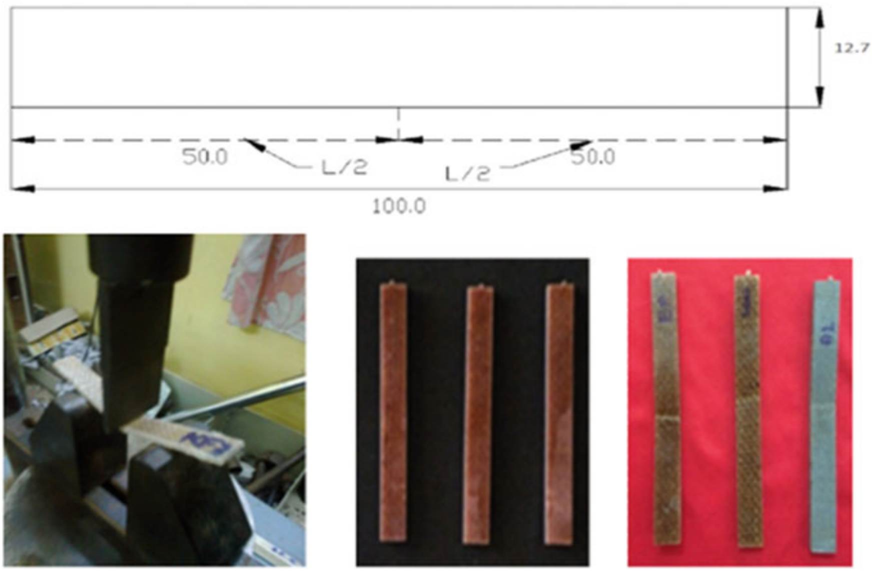


Fig. 7 Flexural test machine and specimens before and after flexural test

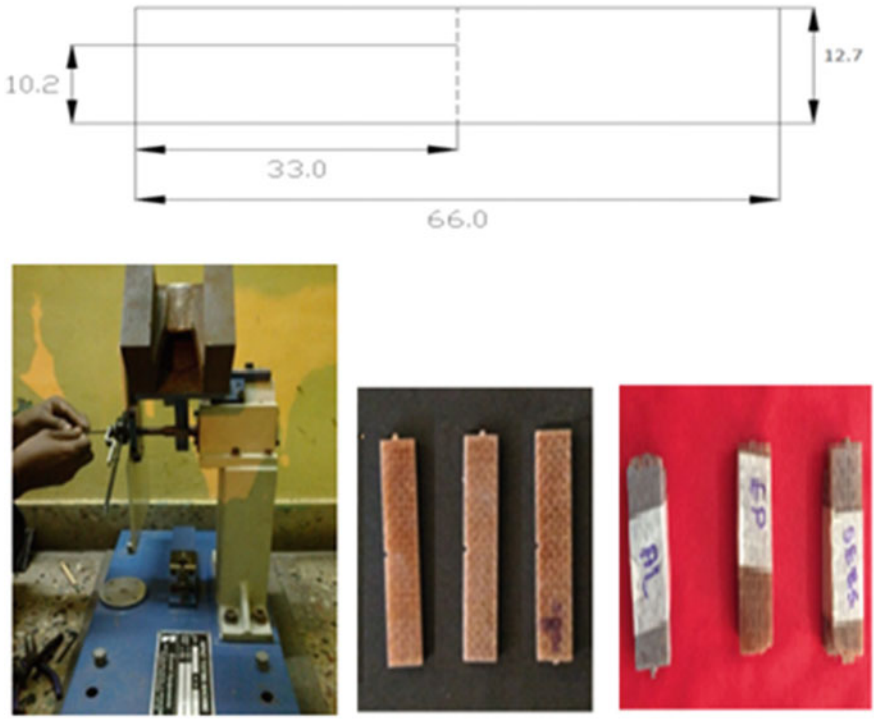


Fig. 8 Impact test machine and specimens before and after impact test

3.3 Impact Test

The test specimens are prepared according to ASTM D256. A hammer force of 7.5 J is given on the specimen. Impact test machine and specimens with dimensions are shown in Fig. 8.

3.4 Shore D Hardness Test

The hardness test specimens are prepared for testing the hardness of the composites, using Durometer. Durometer is typically used to measure the hardness of polymers, elastomers and rubbers. Shore D test machine and specimens are shown in Fig. 9.

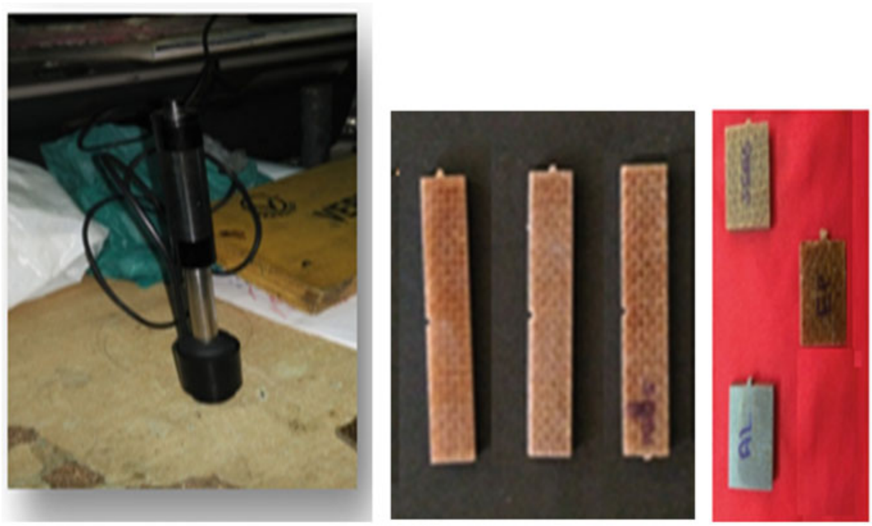


Fig. 9 Shore D hardness tester and specimens before and after test

4 Results and Discussions

Natural fibers are finding increased applications because they are biodegradable, pollution free and cheaper. Nowadays, natural fibers are replacing the use of synthetic fibers in composite fabrication. In this study, three types of composites are fabricated and tested to analyse the effect of epoxy, SEBS and Al on their mechanical properties.

4.1 Tensile Test Results

The tensile test results are presented in Table 1.

From Table 1 it is observed that breaking load for JE is found to be 1720 N, JES is found to be 1833.3 N and for JEA is 1833.3 N. It shows the addition of SEBS/Al increases the breaking load of the composites. Also, there is an increase in ultimate strength and breaking stress of JES and JEA composites. It is also observed that the percentage elongation of JES is higher than the other two types of composites. From the Table 1 it is observed that the displacement is higher for JES and JEA composites.

The comparison graphs for breaking load, ultimate tensile strength, breaking stress and percentage elongation are presented in Fig. 10a–d. From Fig. 10a it is observed that the breaking strength is comparatively higher for JEA followed by JES composite than the JE composite. The ultimate tensile strength (Fig. 10b) is comparatively higher for JEA composite followed by JES than the JE composite. The breaking stress (Fig. 10b) is comparatively higher for JEA composite followed by JES than

Table 1 Tensile test results

Trails	Breaking load (N)			Ultimate Strength (N/mm^2)			Breaking Stress (N/mm^2)			Elongation (%)			Displacement (mm)		
	JE	JES	JEA	JE	JES	JEA	JE	JES	JEA	JE	JES	JEA	JE	JES	**JEA**
1	1350	1820	1920	22.6	30.4	31.1	22.6	30.4	31.1	1.7	4.17	3.33	1.7	3.17	2.37
2	2020	1970	1970	33.8	32.9	32.9	33.8	32.9	32.9	2.5	3.33	3.95	2	2.37	2.67
3	1790	1710	1910	29.9	28.6	31.1	29.9	28.6	30.9	2	5	3.33	1.8	4.71	2.27
Ave	1720	1833	1933	28.8	30.7	31.7	28.8	30.7	31.7	2.1	4.16	3.53	1.8	3.41	2.43

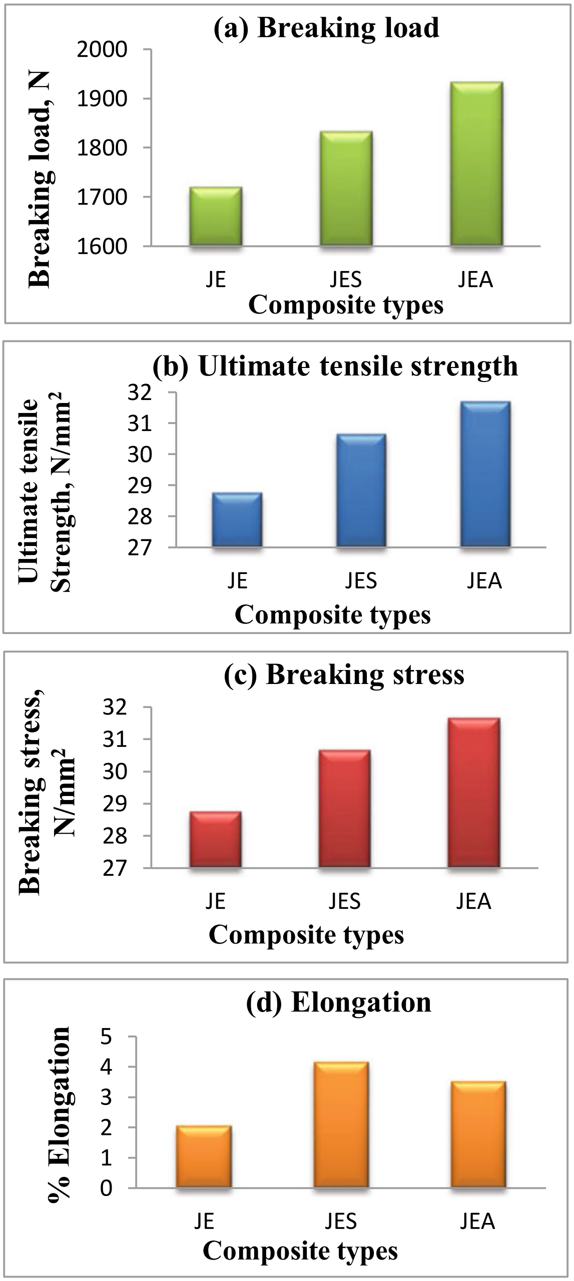


Fig. 10 Comparison graph for **a** breaking load **b** ultimate tensile strength **c** breaking stress **d** elongation

the JE composite. The percentage elongation (Fig. 10d) is comparatively higher for JES followed by JEA than the JE composite. From the test results of the three types, the addition of SEBS/Al with epoxy resin shows improved tensile properties.

4.2 Flexural Test Results

Table 2 shows the results of the test performed on the JE, JES and JEA composite specimens. It is observed that the breaking load of JES and JEA is increased with the addition of SEBS/Al. The ultimate stress of JES is higher than the JE and JEA composites.

The comparison graphs for breaking load, ultimate tensile strength, breaking stress and percentage elongation are presented in Fig. 11a, b.

Table 2 Flexural test results

Trails	Breaking load (N)			Ultimate stress (N/mm^2)		
	JE	JES	JEA	JE	JES	JEA
1	215	230	245	4	4	4
2	220	240	225	3	4	4
3	230	200	220	4	4	3
Ave	221.67	233.33	230	3.67	4	3.67

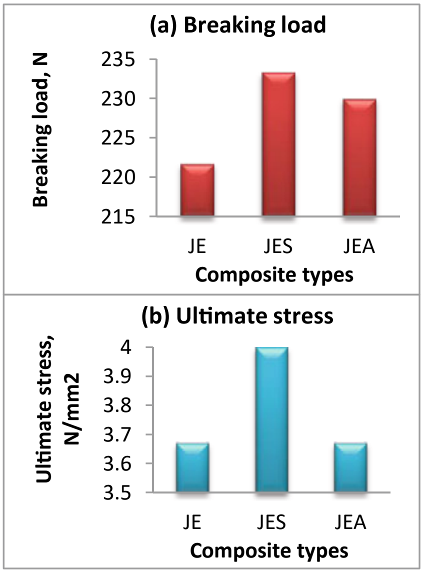


Fig. 11 Comparison graph for **a** breaking load **b** Ultimate stress

From Fig. 11a it is observed that breaking strength is comparatively higher for JES followed by JEA than the JE composite. The addition of SEBS/Al increases the braking strength and the ultimate stress (Fig. 12b) is comparatively higher for JES than the JE and JEA composites.

From the flexural test results of the three types of compo-sites, it is revealed that the addition of SEBS with epoxy resin improves the flexural properties of the jute fiber composite panel.

The graphs of tensile and flexural test are presented in Fig. 12.

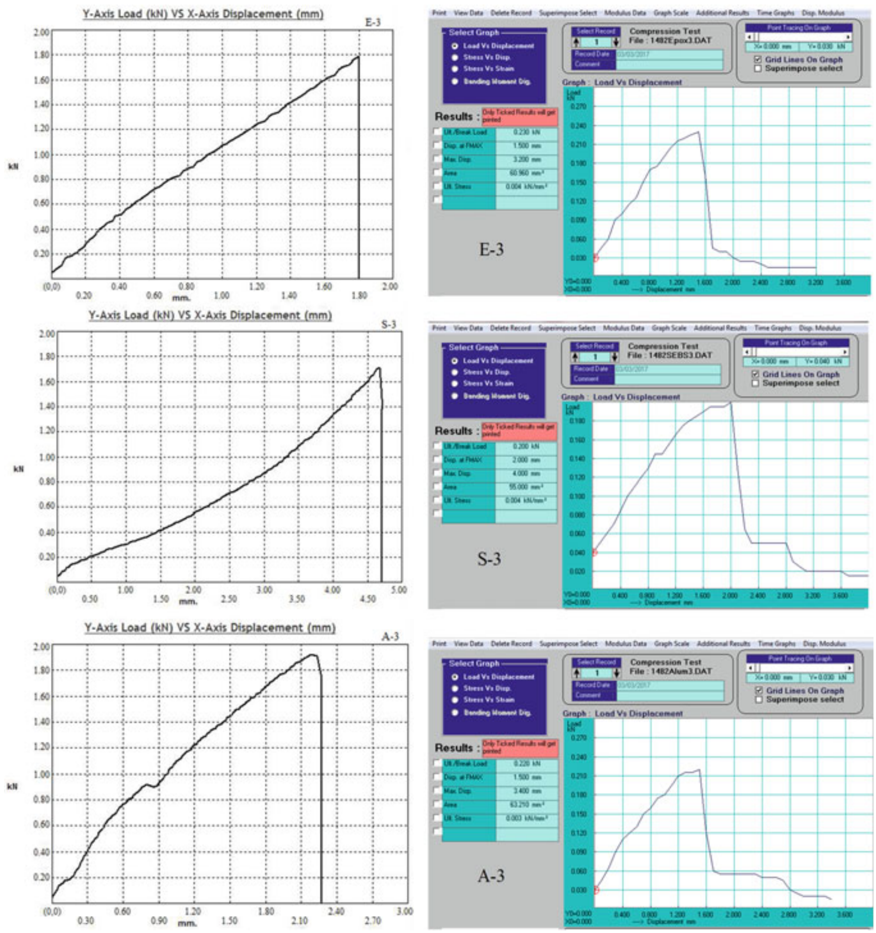


Fig. 12 Typical load–displacement graphs of tensile and flexural test for JE/JES/JEA composite panels

4.3 *Impact and Hardness Test Results*

The impact and hardness test results of three kinds of composites are presented in Table 3. Impact test and hardness graphs are drawn as shown in Fig. 13a, b. From Fig. 13a it is observed that the impact strength is comparatively higher for JEA than the other two types. The hardness (Fig. 13b) is comparatively higher for JE followed by JEA than the JES composite.

Table 3 Impact and hardness test results

Trails	Impact values (J)			Hardness values		
	JE	JES	JEA	JE	JES	JEA
1	0.5	0.4	0.5	62.3	64.8	66.7
2	0.4	0.4	0.5	65.4	60.8	60.1
3	0.4	0.5	0.5	62.7	60.2	62.8
4	–	–	–	63.5	60.7	58.1
Ave	0.43	0.43	0.5	63.475	61.625	61.925

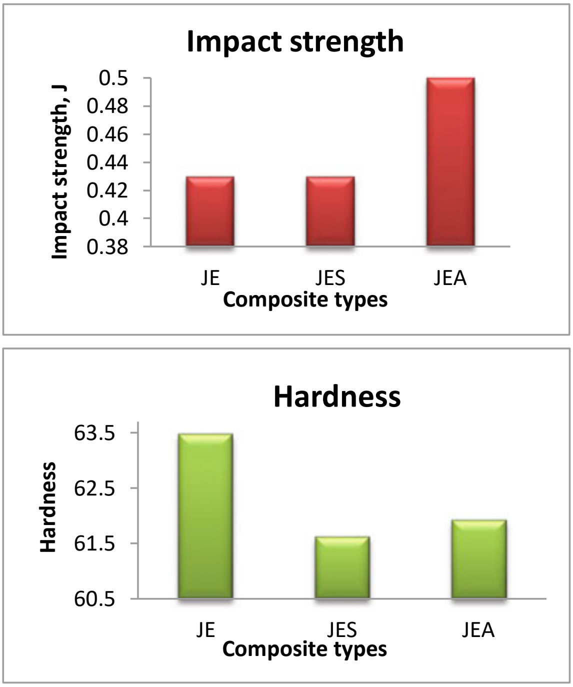


Fig. 13 Comparison graph for **a** impact test **b** hardness

5 Conclusion

In this study the woven Jute fiber composite panels of three kinds such as JE, JES and JEA fabricated and the mechanical properties have been tested using various tests. The results have been compared to analyse the effectiveness of epoxy, SEBS and Al metal powder in the Jute fiber composites. The conclusions arrived are:

- The tensile breaking strength, ultimate tensile strength and breaking stress are comparatively higher for JEA followed by JES than the JE composites. And also it is observed that the percentage elongation is comparatively higher for JES followed by JEA than JE composites.
- The flexural breaking strength of JEA and JES composites are comparatively higher than the JE composites and the ultimate stress of JES is comparably higher.
- The impact strength is comparably higher for JEA than the other two composites.
- The hardness value is comparably higher for JE than the other two composites.

From this investigation, it is concluded that SEBS/Al improves the mechanical properties of the fabricated composite panels. Natural fiber composites are found to be an alternate for synthetic fibers as they are environmental friendly and biodegradable. The jute fiber with epoxy composites (JE) are already used in cars as door/ceiling panels, insulating panels and also in structural applica-tions. The newly fabricated JES and JEA composites can have prom-ising future applications. Further research work is needed in this field to improvise the proper composition of these elements for the best outcome.

References

1. Ajith Gopinath M, Kumar S, Elayaperumal A (2014) Experimental Investigations on mechanical properties of jute fiber reinforced composites with polyester and epoxy resin matrices. Procedia Engineering 97:2052–2063. https://doi.org/10.1016/j.proeng.2014.12.448
2. Souza BR, Benedetto RMD, Hirayama D, de Andrade O, Raponi LC, Barbosa M, Junior ACA (2017) Manufacturing and characterization of jute/pp thermoplastic commingled composite. Mater Res 20(2):458–465
3. Gon D, Das K, Paul P, Maity S (2012) Jute Composites as wood substitute. International Journal of Textile Science 1(6):84–93
4. Iqbal N, Mousumi JF, Islam AM (2017) Effect of fiber length on properties of jute fiber reinforced polymer matrix composite. International Journal of Industrial Engineering 1:201–207
5. Santos LF, da, Lima Junior Edio Pereira, Louro Luis Henrique Leme, and Monteiro Sergio Neves. (2015) Ballistic test of multi layered armor with intermediate epoxy composite reinforced with jute fabric. Mater Res 18:170–177
6. Md. Rafiquzzaman, Md. Habibur Rahman, Md. Abu Sayeed and Md. Nawazish Ali. 2016. Evaluation of mechanical behavior of jute fibre-aluminum powder reinforced hybrid polymer composites. International Journal of Mechanical Engineering and Automation 3: 202-207
7. Palanikumar K, Valarmathi TN (2016) Experimental investigation and analysis on thrust force in drilling of wood composite medium density fiberboard (MDF) panels. Exp Tech 40:391–400

8. Pereira, T. G. T., J.F. Mendes, J.E. Oliveira, J.M. Marconcini, and R.F. Mendes. 2018. Effect of reinforcement percentage of eucalyptus fibers on physico-mechanical properties of composite hand lay-up with polyester thermosetting matrix. Journal of Natural Fibers. 1–11
9. Sivasubramanian. P, A, Alavudeen, and M. Thiruchitrambalam. 2011. Mechanical properties of natural-fibre-reinforced composites.
10. Berhanu T, Kumar P, Singh I (2014) Mechanical behavior of jute fiber reinforced polypropylene composites. 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12th–14th, 2014, IIT Guwahati, Assam, India 289: 1–6. Valarmathi, T.N., K. Palanikumar, and S. Sekar, 2013a. Thrust Force Studies in Drilling of Medium Density Fiberboard Panels. Advanced Materials Research 622–623:1285–1299
11. Valarmathi TN, Palanikumar K, Sekar S (2013) Prediction of parametric influence on thrust force in drilling of wood composite panel. International Journal of M M M Eingineering 1:71–74
12. Valarmathi, T.N.; Palanikumar, K.; Latha. B. 2013c. Measurement and analysis of thrust force in drilling of particleboard (PB) composite panels.
13. Valarmathi TN, Palanikumar K (2013) Studies on delamination in drilling of Particleboard (PB) wood composite. Proc Indian Natl Sci Acad 79(3):339–345
14. Valarmathi TN, Sekar S, Palanikumar K (2015) A review on modelling and optimization of machining characteristics of composites. Int J Appl Eng Res 10(11):10419–10424

Mechanical and Resonance Properties of Sustainable Polymer Composite Reinforced with Unidirectional Bio Palm Fiber

S. Vijayakumar, K. Palanikumar, and Elango Natarajan

Abstract The use of natural fibers to reinforce polymer matrix, called as green engineering has recently attracted the industries for their high specific strength, low weight and biodegradability etc. Palm fibers at 10, 20, 30, 40, 50 and 55wt% are used to synthesize the eco-friendly composites. The mechanical properties of composites are investigated according to the respective ASTM standards. The vibration characteristics such as the resonance frequency and damping coefficient composites are determined through experimental modal analysis. The morphological structure, internal cracks, mechanism of failure of the composites are examined and presented. The best mechanical properties and damping coefficient are observed from 50wt% of fibers loaded bio-composite. The increase of fillers more than 50wt% starts decreasing the properties and hence the highest loading of palm fibers certain to be 50%. The results observed from the examinations will be useful for industries for sustainable design and analysis of their products.

Keywords Polymer composite · Palm fiber · Vibration · Resonance · Green composite

1 Introduction

Many industries prefer to adopt green engineering, because of the high environmental issues that the world faces in recent years. The green engineering expects to incorporate principle of environmentally conscious attitudes and values in each

S. Vijayakumar
Department of Mechanical Engineering, Sathyabama University, Chennai 600 119, India

K. Palanikumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, Chennai 600 044, India

E. Natarajan (✉)
Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur-56000, Malaysia
e-mail: cad.elango.n@gmail.com

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_12

design of the product in industries. The primary objective of it is to have local and global environmental quality. The sustainable design involves use of bio materials, recycled materials or reusable materials in the product design. In addition, the sustainable product design aims for longer life of the product without deploying the nature or environment. One of the plump ways is to use bio-composites in sustainable design that holds safety, health and welfare of the public. The natural fibers reinforced composites are regarded to be light weight, biodegradable strong and free from health hazards that serves to be solution to the environmental exterminate. These materials have the potential to be used in automobiles, aerospace, leisure, constructions, sports and packaging.

Mominul Haque et al. [1] used chemically treated raw palm fibers and coir fibers to prepare reinforced polypropylene (PP) bio-composite. Benzenediazonium was used to improve the compatibility of filler with the base matrix. They revealed that chemically treated coirs of 30wt% yielded the better mechanical properties. They also revealed that the increase of hydroxyl group increased the filler loading and meanwhile, decreased the respective moisture absorption compared to virgin material. Velmurugan and Manikandan [2] used palmyra fibers and glass fibers to reinforce Rooflite resin and conducted mechanical tests and water absorption studies. They revealed that addition of glass fibers could increase mechanical properties, but decrease water absorption. Jawaid et al. [3, 4] prepared jute and palm fibers reinforced polymer composite and reported that elastic modulus, viscous modulus, strength and damping ratio were increased in the effect of fillers.

Ramesh et al. [5] attempted to develop reinforced polyester composite with sisal, jute and glass fibers. They prepared hybrid composites with different combination of these fillers and reported that sisal and jute reinforced polyester composite is the one resulting a higher strength than any other combination of fillers. Arthannarieswaran et al. [6] studied the effect of banana fibers, sisal fibers and woven E-glass fibers in epoxy. They revealed that the strength of the composite could be improved by the addition of many layers of glass fibers into the matrix. Also reported that flexural strength was enhanced due to the addition of banana and sisal fibers and the hybridization of such natural and synthetic fillers in the composite laminate is suitable only for medium load applications and non-bio related applications. Ratna Prasad and Mohana Rao [7], evaluated and reported the superior properties of Jowar fibers with Sisal and bamboo fibers. The composites were prepared with unidirectional reinforcement of fibers in polyester matrix through hand lay-up method. They also reported that unidirectional arrangement of fibers increases properties of the composite as the deformation is minimum.

It was observed that choice of fibers and the volume fraction are most important factors affecting the properties of the resultant composites. The short fibers are better than long fibers as they result better mechanical properties. Moreover, the extraction of short fibers is simpler than long fibers. Gupta and Srivastava [8] evaluated unidirectional reinforcement and mat form reinforcement of sisal fibers into epoxy matrix and reported that unidirectional is better than mat form in regard of achieving high mechanical properties. Venkateshwaran et al. [9] used rule of hybrid mixture to blend sisal and banana short fibers with epoxy composite. They reported random oriented fibers resulted better mechanical properties. Nilza et al. [10] evaluated the use of bagasse, banana trunk and coconut coir fibers for medium strength application scoping to use in automobile interior parts. Cao et al. [11] reported that alkali treated bio composite results high mechanical properties. Okubo et al. [12] attempted to reinforce steam exploded bamboo fibers with PP matrix and concluded that steam explosion method is better to extract bamboo fibers. Albuquerque et al. [13] reported the effect of jute rover fibers in polyester in terms of mechanical properties and wettability. Nair et al. [14] revealed that benzoylation of sisal fibers results the better mechanical properties for polystyrene/sisal composite. Jacob et al. [15] used sisal and palm fibers to prepare hybrid fiber reinforced rubber composite and reported that resorcinol-hexamethylene tetramine bonding is suitable for improving the fillers-matrix interface. Geethamma et al. [16] attempted short coir fibers to reinforce rubber and revealed that energy dissipation is higher at poor interface. Also added that the viscous modulus and glass transition temperature are increasing as the coir filler reinforcement increases. Lovino et al. [17] used PLA, thermoplastic starch and coir fibers to prepare bio composites and investigated the biodegradation of the material. Brahmakumar et al. [18] used coconut fibers to reinforce low density polyethylene matrix and studied the effect of wax surface of the fibers in interfacial bonding. Harish et al. [19] conducted qualitative studies and reported that coir fibers will be a good alternative for glass fibers and carbon fibers. Valadez-Gonzalez et al. [20] reported that alkali soluble compounds and the limited amount of lignin from henequén fibers increases the adsorption of silane coupling agent. Vijayakumar et al. [21] used the hybrid filler of caryota-glass and bamboo-glass fibers to reinforce the epoxy matrix. They reported that bamboo-glass fibers reinforced polymer composite has higher tensile properties, while caryota-glass fibers reinforced composite has higher flexural strength and impact strength. In their another study [22], they reported that 40wt% reinforcement of caryota fibers into the polymer matrix yields the better mechanical properties.

Palm fibers are considered to be potential fillers for resulting high strength and modulus.Goulart et al. [20] developed palm fibers reinforced polypropylene (PP) composite to study the effect of fillerson properties. Palm fibers abundantly available in southern India. They can be found from various parts of Palm tree (Borassus flabellifer).The current research is focused on using abundantly existing palm fibers for reinforcing epoxy resin and check for its effect on mechanical and vibrational properties.

2 Materials and Methods

Palm fibers (Palmaceae) were received from the place called Karungal, Kanyakumari District in India. Epoxy(LY556) resin and the catalyst araldite (HY951) as a hardener were purchased from a resin supplier in India. The density of the epoxy resin and hardener were 1.15 to 1.20 g.cm^{-3} and 0.97 to 0.99 g.cm^{-3} respectively. These palm fibers from palm trees were extracted by exposing them into water followed and by hand-picking. The extracted fibers were soaked into water for a week time and dried in sunlight for about two weeks after thorough cleaning to remove moisture content. The experimentally determined properties of palm fibers is presented in Table 1.

Firstly, Epoxy LY556 was mixed with HY951 in the weight ratio of 10:1. Meanwhile, araldite was added as 1% to the resin-catalyst mixture. The resin matrix was poured into a mold of stainless steel in the dimensions 290 mm × 290 mm × 3 mm. The unidirectional palm fibers of 290 mm in length were cut and prepared for the reinforcement. The various weight fraction of natural fibers; 10, 20, 30, 40, 50 and 55wt% were added into the epoxy matrix in order to prepare specimen of different reinforcement. Once the matrix-filler were arranged in the mold, the compression molding was carried out at 9.8 N/mm^2 and 75° Celsius for 20 minutes. The curing of the composite was performed for about 1 hour after the compression molding. The prepared polymer matrix composite was removed from the mold after curing using releasing agent.

The dimension of prepared natural fibers reinforced composites was 270 mm × 270 mm × 3 mm. The composite in different % of reinforcement were cut into the required dimension for different mechanical tests.

Samples of 25 mm in width, 3 mm in thickness and 250 mm in length were uniaxially loaded at 2 mm/minute according to ASTM D3038. Five samples in the same weight fraction were tested one after another. The load–displacement data for each specimen was recorded from which mean elastic modulus, % elongation at break and ultimate strength was computed.

Samples of 25 mm in width, 3 mm in thickness and 125 mm in length were transversely loaded at 2 mm/minute in comply with ASTM D790 standards. Five samples in the same weight fraction were tested one after another and their respective flexural modulus and flexural strength were noticed.

ASTM D256 was followed for carrying out Izod impact test. The competence of the material to absorb energy during a collision or sudden impact load is generally determined in impact tests. This test is required for the application like vehicular collision, where the material undergoes a very rapid deformation. The pendulum load was released from the known height to the attached sample in order to collide

Table 1 Physical properties of palm fibers used in the composite

Description	Value
Density(g/cm3)	1.2–1.3
Cellulose(%)	28
Hemi cellulose(%)	25
Lignin(%)	45
Tensile strength(MPa)	220
Elastic modulus(GPa)	4.8
Percentage of Elongation(%)	2.84
Percentage of Moisture content(%)	11

and fracture the sample. Five samples in each composition were tested in the similar manner and the respective absorbing energy was measured.

The resonant frequency and damping factor of palm fibers reinforced polymer composite were determined through the vibration testing experiment. The machine consists of tri axial accelerometer, impulse hammer, sensors, data acquisition system (DAS) and DEWE Soft 7 software for acquisition of data. The dimension of the polymer composite laminate was 200 mm × 20 mm × 3 mm. It was firstly clamped to cantilever beam set up using a "C" clamp. The tri-axial accelerometer was then attached to the composite laminate sample with the help of wax. An impact force was applied using impulse hammer and the vibrating signal produced by the load was sensed by tri axial accelerometer. The respective data was captured by DAS, which was then converted to frequency response time function by DEWE Soft7.

The damping factor(ζ) of the palm fibers reinforced polymer matrix composite was determined using the below Eq. (1).

$$\zeta = \frac{\Delta\omega}{2\omega_n} \tag{1}$$

where ζ = Damping factor.
$\Delta\omega$ = Band width.
ω_n = Natural frequency.

3 Results and Discussions

3.1 Tensile Properties

Figure 1 presents the tensile strength of palm fibers reinforced epoxy composites at different fiber loading. Figure 2 shows load–displacement graph and stress–strain graph of epoxy/50wt% palm fibers composite during tensile test. The graph shows that the strain increases proportional to stress up to 70.5 MPa, beyond which, it drops at the percentage of strain rate of 5.66. The experimental results indicate that the reinforcement of 50wt% palm fibers yields the highest tensile strength of 70.75 MPa than any other samples. The strength got decreased beyond 50wt% of filer reinforcement. This could be due to the brittle nature received by the resultant composite at higher fillers loading and moreover the poor attachment of filler to the polymer matrix. Hence it is concluded that the maximum of 50wt% is the best reinforcement percentage to have the best result. Comparing the current results with [21], it is noticed that the strength of 50wt% palm fibers reinforced epoxy composite is 31% more than that of caryota fibers reinforced composite. Also the palm fiber reinforced epoxy composites is 78.1% more than that of palmyra/glass hybrid fibers reinforced composite developed by Velmurugan and Manikandan [2].

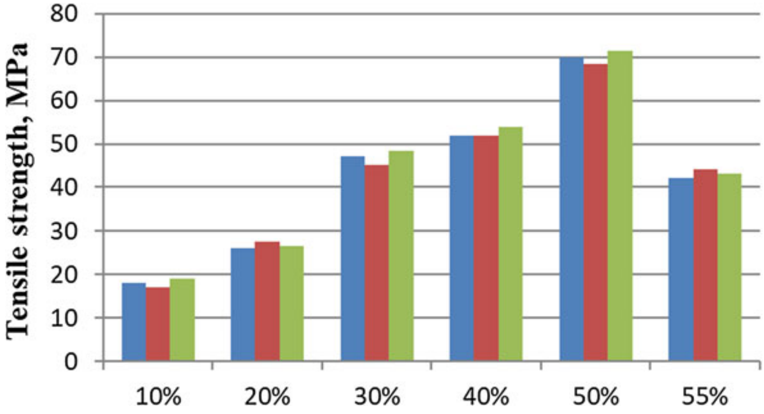
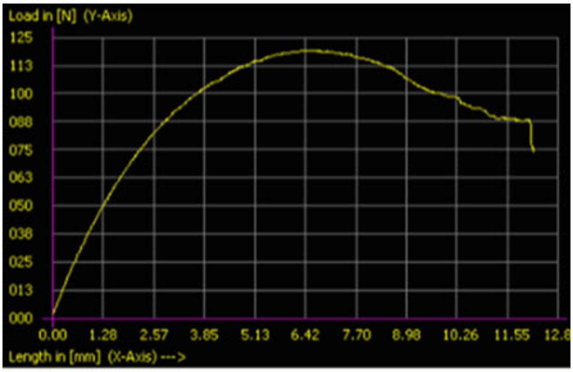
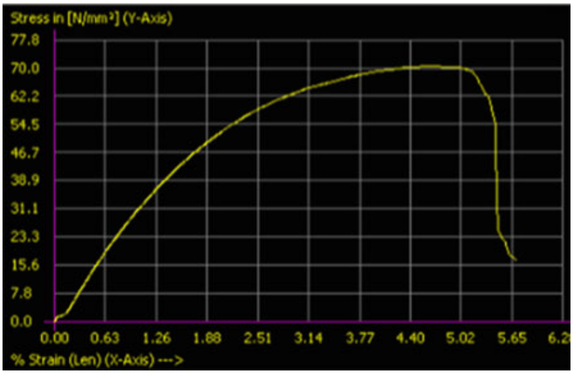


Fig. 1 Tensile strength of palm fibers reinforced epoxy composite



(a)



(b)

Fig. 2 Tensile test results of epoxy/50wt% palm fibers bio composite **a** Load–displacement graph **b** Stress–strain graph

According to Harish et al. [8], the tensile strength of 50wt% chopped coir fibers reinforced polymer composite is 17.86 MPa which is 3.9 times lower than the current result.

3.2 Flexural Properties

Load-displacementof epoxy/50wt% palm fibers composite is shown in Fig. 3 The result infers that the lateral displacement is increased with the increase of applied load up to 105.92 N, beyond which, it is decreased. The sample fractured at the maximum displacement of 9.2 mm. Figure 4 shows the bending strength of composites at different fiber loading. It is noted that the flexural strength and flexural modulus are getting increased up to 50wt% of filler loading. The highest flexural strength of 82.5 MPa was recorded by 50 wt% fillers reinforced composite.

It is perceived that the bearing strength of 50wt% palm fibers reinforced composite is 72% more than that of treated 30wt% palm fibers and 62% higher than 30 wt% coir reinforced composites [1]. It is also observed that the flexural strength of 50wt% palm fiber composites is 52% more than that of 55wt% palmyra/glass fiberreinforced hybrid composite [2]. The current result is 2.76% higher than results published by Harish et al. [18] and is 13% higher than that of caryota fibers reinforced composites [21].

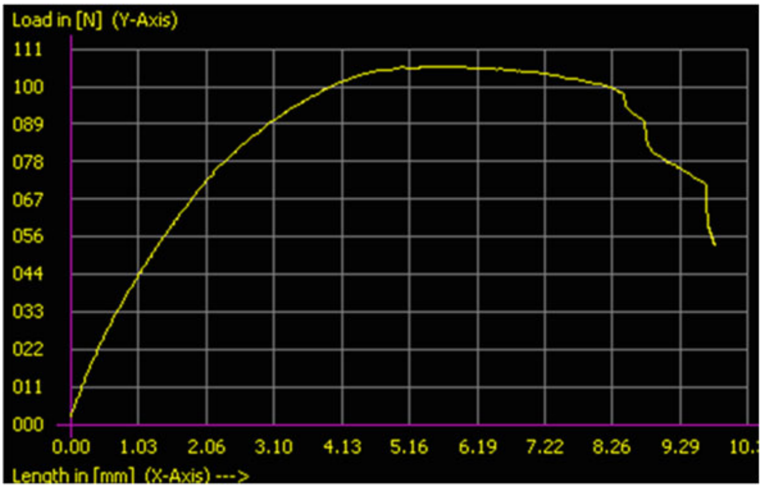


Fig. 3 Load–displacement graph of epoxy/50wt% palm fibers bio composite drawn from flexural test

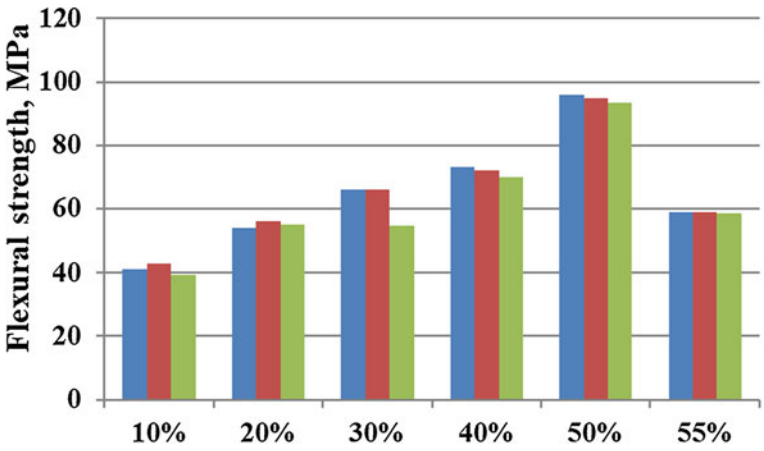


Fig. 4 Flexural strength of palm fibers reinforced epoxy composite

4 Impact Properties

Figure 5 shows impact strength measured for different wt% of palm fibers reinforced epoxy composite. The trend of the results is similar to tensile strength and flexural strength discussed in previous sections. The impact strength increases gradually at the loading of palm fibers and the highest impact strength was recorded as 3.37 J for 50wt% palm fibers reinforced composite. Mominal Haque et al. [1], observed the impact strength decrease beyond 35wt% of fiber loading, but, in the current research, the impact strength keeps increasing upto 50wt% of palm fibers. These results asserted that the palm fibers are capable for absorbing energy, as there is

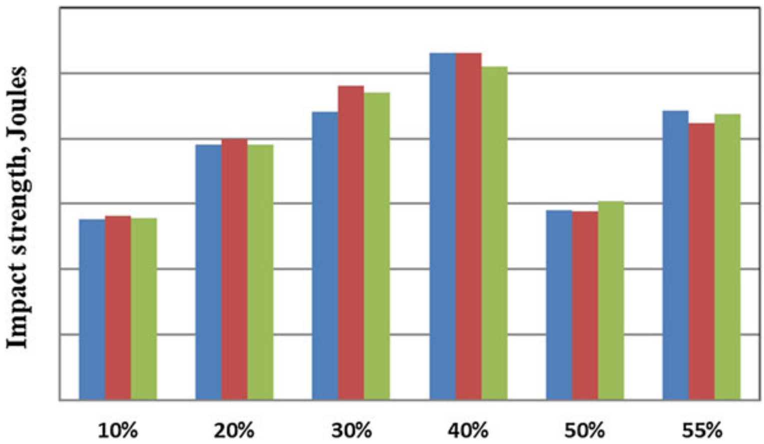


Fig. 5 Impact strength of palm fibers reinforced epoxy composite

Table 2 Resonance frequency and damping factor of respective wt% of palm fibers reinforcement

Wt% of palm fibers	Resonance Frequency (Hz)			Damping factor		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
10	7.32	14.65	3.06	0.000255	0.00026	0.000126
20	14.08	36.89	73.34	0.095	0.087	0.076
30	15.98	87.89	134.09	0.038	0.066	0.0136
40	19,53	165.98	253.85	0.0074	0.008	0.0098
50	17.09	271.00	358.89	0.075	0.0902	0.0652
55	17.11	63.64	144.48	0.331	0.111	0.153

a strong matrix-fibers bonding. In most of past research except research done by Elango et al. [23] commented that low loading of fillers will result good result. From the above examinations, it is concluded that high loading of palm fibers is possible and also it will give high mechanical properties.

4.1 Modal Analysis

Table 2 depicts the modal characteristics; resonance frequency and damping coefficient of unidirectional palm fibers reinforced epoxy composite. The results revealed that the resonance frequency and damping factor depends upon the wt% of palm fibers loading of the composite laminates. The best damping factors was resulted by 50 wt% of fiber loading, beyond which, natural frequencies and damping factors started decrease. The best results noticed in 50wt% is caused by the better interfacial bonding between the fibers and matrix, which is evidenced in other mechanical tests as well. Obviously, the dynamic characteristic mainly depends on stiffness and moment of inertia and mass density of the composites (Fig. 6).

4.2 Scanning Electron Microscopic (SEM) Analysis

The morphology of the fractured samples from tensile, flexural and impact tests were examined. This was done to analyse the fiber pull-out, interfacial gap in the cross section of the fractured samples. The setting used for scanning the image is: resolution = 2.0 μm, magnification = 5 × to 250x, WD = 20 mm or less, electron gun accelerating voltage = 0.5 to 20 kV, and pre-centered tungsten hairpin filament.

SEM images were taken from broken samples in each wt% to investigate the surface texture, internal cracks and failure mechanism,interfacial properties etc.of the fractured sample. Figure 7a, b show the fractured surface of 50wt% fibers reinforced epoxy composite in low (×80) and high magnification (×250) respectively. It shows voids and discontinuity in the tensile specimen that caused by breakage of individual

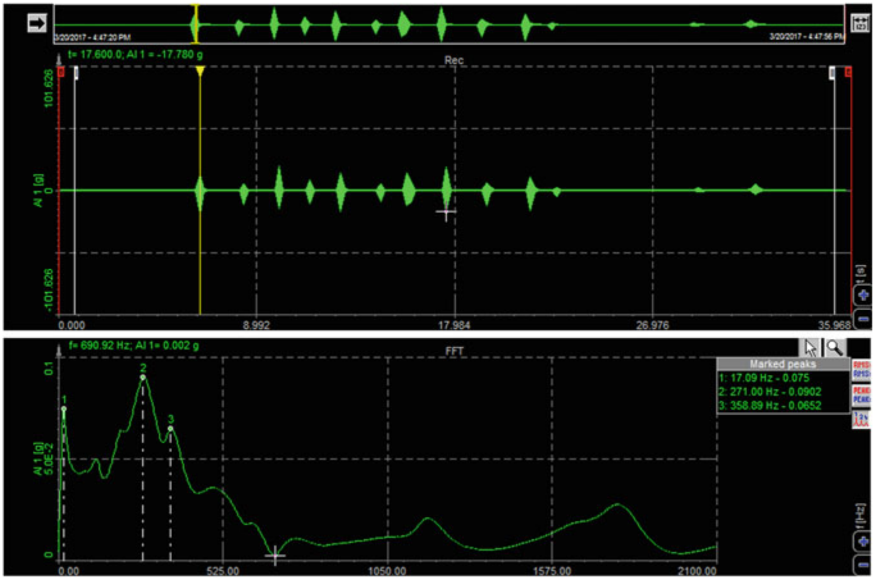


Fig. 6 50 wt% palm fibers reinforced composite: amplitude versus time and amplitude versus frequency

fiber and appreciable delamination from strong bondbetween fiber and matrix. The strong matrix-fibers interface is the cause for having the highest tensile strength [24].

Figure 8a, b illustrates the SEM image of 50wt% palm fibers reinforced composite specimen after flexural test. It indicates the fracture occurred in fiber bundle and the discontinuity in fiber and matrix. It also evidences the close pack of bonding between palm fibers and the polymer matrix. It is observed from the transverse cross-section of the sample that there is no fiber pullout which ensures the enhancement of the material property of the composite. It is understood that the palm fibers took a homogeneous distribution over the polymer matrix that led to better fibers-matrix bonding. And hence it caused the increased flexural strength of palm fibers reinforced epoxy composite.

Figure 9 shows the SEM image of 50 wt% palm fiber reinforced composite after the impact test. The porous cross section of the fibers is observed that caused more area of contact between the fibers and matrix. The unidirectional fibers reinforcement resulted in no voids and defects, and avoided the premature failure of the composite. These reasons caused the improved impact strength, which represents the toughness of composite laminates.

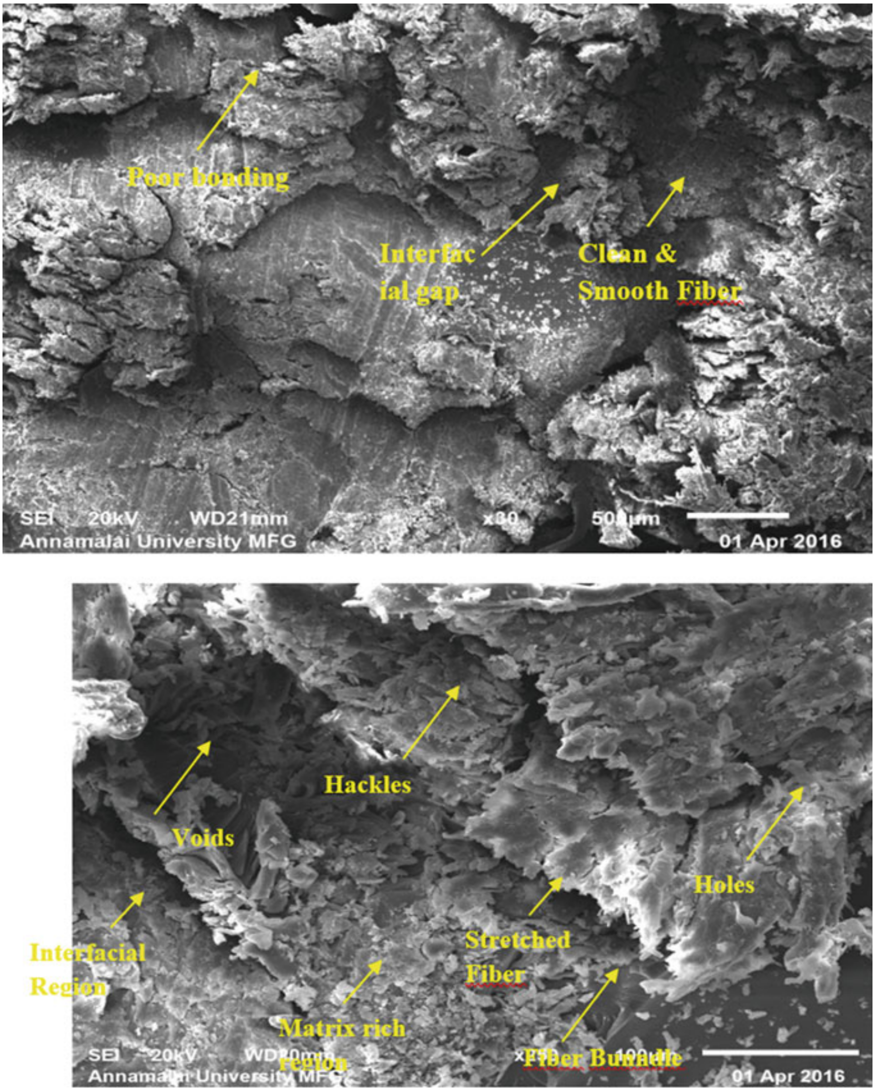


Fig. 7 Scanning electron micrographs of 50 wt % palm fibers reinforced composite specimen after tensile fracture **a** low magnification of x 80 **b** at x250

5 Conclusions

In this research, unidirectional palm fibers reinforced epoxy bio-composites was prepared through compression molding. It is concluded from the investigations that 50wt% of palm fibers reinforcement is the best to have highest mechanical properties. The respective resonance frequencies and damping factors were estimated through

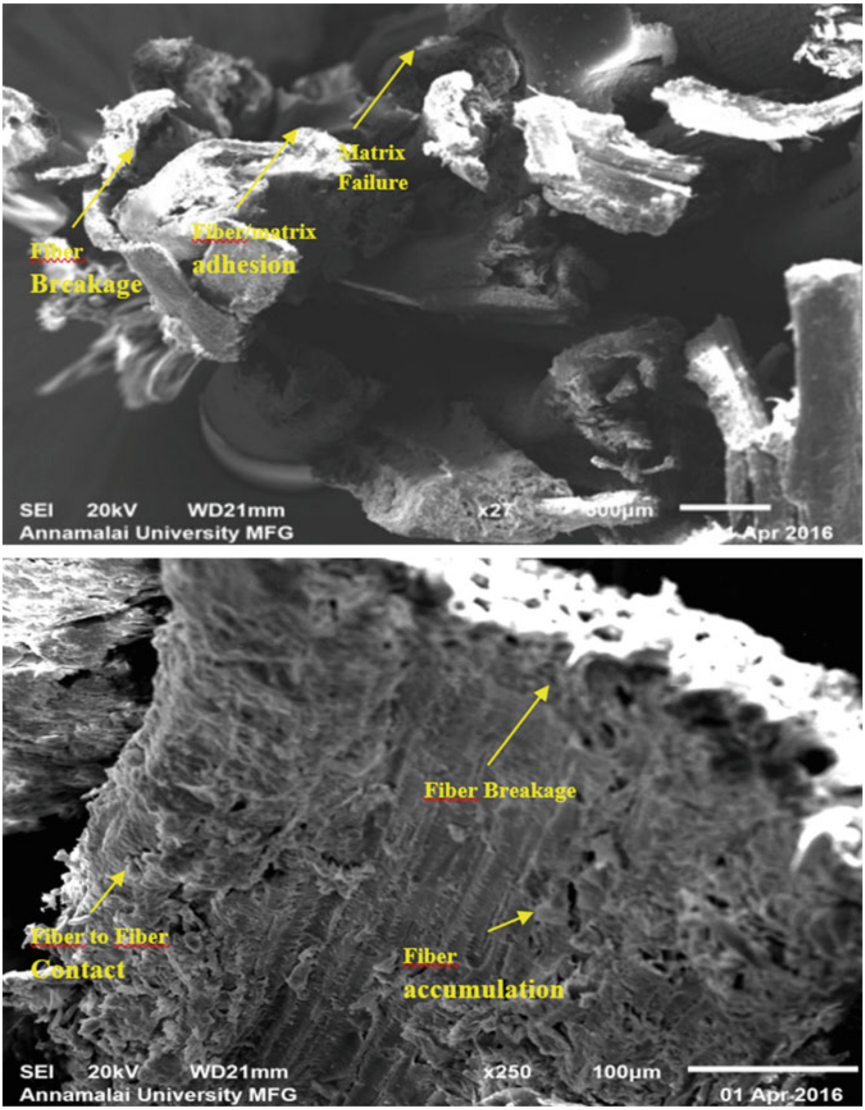


Fig. 8 Scanning electron micrographs of 50 wt% palm fibers reinforced composite specimen after flexural test of x 80 **b** at x250

modal analysis. Since palm fibers are abundantly available and cheaper, they can be used as bio resources to prepare sustainable materials. Industries can use the presented material properties and resonance frequencies for product design. These data will assist in mechanical model, static and dynamic analysis of the component. Particularly,these polymer fibers reinforced polymer composite can be used for developing interior automobile vehicle and housing sectors.

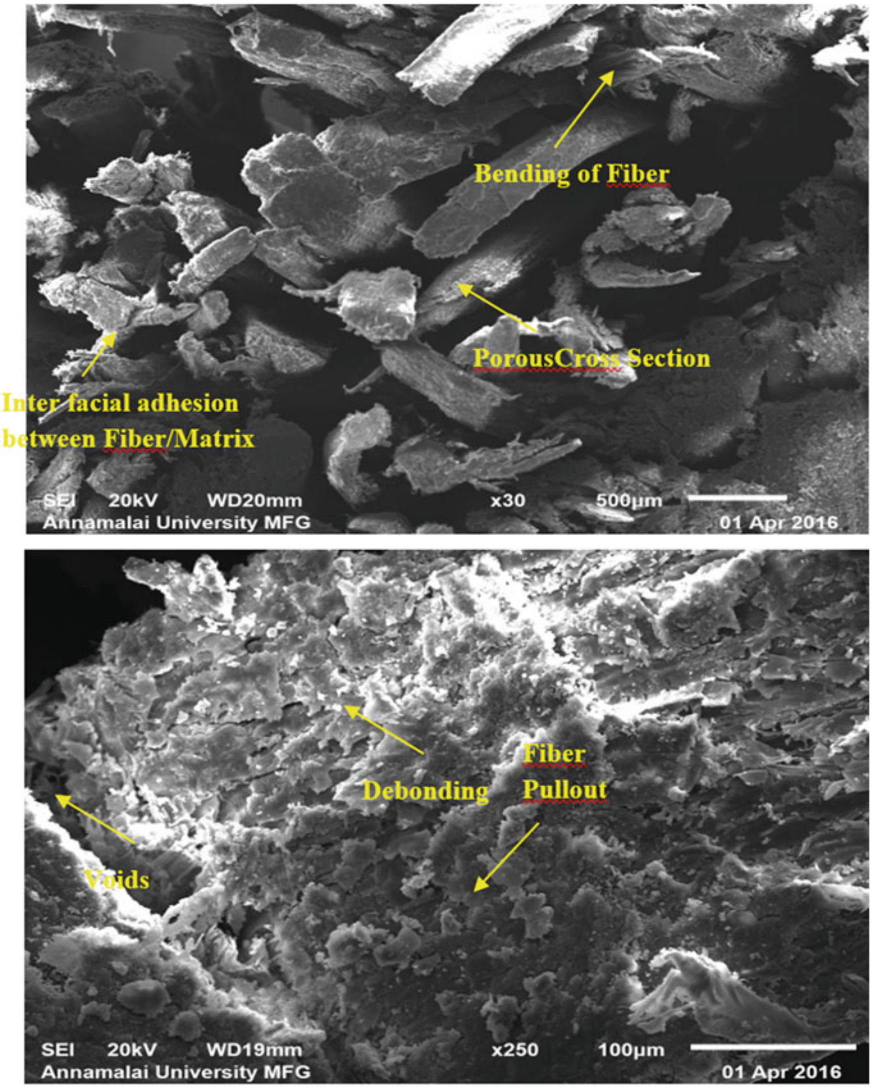


Fig. 9 Scanning electron micrographs of 50 wt% palm fibers reinforced composite specimen after impact test of x 80 **b** at x250

References

1. Haque MM, Hasan M, Islam MS, Ali ME (2009) Physico-mechanical properties of chemically treated palm and coir fiber reinforced polypropylene composites. Bioresour Technol 100:4903–4906
2. Velmurugan R, Manikandan V (2007) Mechanical properties of palmyra/glass fiber hybrid composites. Compos Part A Appl Sci Manuf 38:2216–2226
3. Jawaid M, Abdul Khalil HPS, Hassan A, Dungani R, Hadiyane A (2013) Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites. Compos Part B Eng 45:619–624
4. Jawaid M, Abdul Khalil HPS, Abu Bakar A (2011) Woven hybrid composites: Tensile and flexural properties of oil palm-woven jute fibres based epoxy composites. Mater Sci Eng A 528:5190–5195
5. Ramesh, M., Palanikumar, K., Reddy, K. & Hemachandra; (2013). Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites.
6. Arthanarieswaran VP, Kumaravel A, Kathirselvam M (2014) Evaluation of mechanical properties of banana and sisal fiber reinforced epoxy composites: Influence of glass fiber hybridization. Mater Des 64:194–202
7. Ratna Prasad AV, Mohana Rao K (2011) Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo. Mater Des 32:4658–4663
8. Gupta MK, Srivastava RK (2014) Tensile and Flexural Properties of Sisal Fibre Reinforced Epoxy Composite: A Comparison between Unidirectional and Mat form of Fibres. Procedia Mater. Sci. 5:2434–2439
9. Venkateshwaran N, Elayaperumal A, Sathiya GK (2012) Prediction of tensile properties of hybrid-natural fiber composites. Compos Part B Eng 43:793–796
10. Jústiz-Smith NG, Virgo GJ, Buchanan VE (2008) Potential of Jamaican banana, coconut coir and bagasse fibres as composite materials. Mater Charact 59:1273–1278
11. Cao Y, Shibata S, Fukumoto I (2006) Mechanical properties of biodegradable composites reinforced with bagasse fibre before and after alkali treatments. Compos Part A Appl Sci Manuf 37:423–429
12. Okubo K, Fujii T, Yamamoto Y (2004) Development of bamboo-based polymer composites and their mechanical properties. Compos Part A Appl Sci Manuf 35:377–383
13. de Albuquerque A, Joseph K, Hecker de Carvalho L, D'Almeida JRM (2000) Effect of wettability and ageing conditions on the physical and mechanical properties of uniaxially oriented jute-roving-reinforced polyester composites. Compos Sci Technol 60:833–844
14. Nair KCM, Diwan SM, Thomas S (1996) Tensile properties of short sisal fiber reinforced polystyrene composites. J Appl Polym Sci 60:1483–1497
15. Jacob M, Thomas S, Varughese KT (2004) Mechanical properties of sisal/oil palm hybrid fiber reinforced natural rubber composites. Compos Sci Technol 64:955–965
16. Geethamma VG, Kalaprasad G, Groeninckx G, Thomas S (2005) Dynamic mechanical behavior of short coir fiber reinforced natural rubber composites. Compos Part A Appl Sci Manuf 36:1499–1506
17. Iovino R, Zullo R, Rao MA, Cassar L, Gianfreda L (2008) Biodegradation of poly(lactic acid)/starch/coir biocomposites under controlled composting conditions. Polym Degrad Stab 93:147–157
18. Brahmakumar M, Pavithran C, Pillai R (2005) Coconut fibre reinforced polyethylene composites: effect of natural waxy surface layer of the fibre on fibre/matrix interfacial bonding and strength of composites. Compos Sci Technol 65:563–569
19. Harish S, Michael DP, Bensely A, Lal DM, Rajadurai A (2009) Mechanical property evaluation of natural fiber coir composite. Mater Charact 60:44–49
20. Valadez-Gonzalez A, Cervantes-Uc J, Olayo R, Herrera-Franco P (1999) Chemical modification of henequén fibers with an organosilane coupling agent. Compos Part B Eng 30:321–331

21. Vijayakumar S, Palanikumar K (2019) Mechanical Property Evaluation of Hybrid Reinforced Epoxy Composite. Mater. Today Proc. 16:430–438
22. Palanikumar K, Subbiah V (2019) Bio Caryota Fiber Reinforced Polymer Composites: Mechanical Properties and Vibration Behavior Analysis. J Bionic Eng 16:480–491
23. Elango N, Gupta NS, Lih Jiun Y, Golshahr A (2017) The Effect of High Loaded Multiwall Carbon Nanotubes in Natural Rubber and Their Nonlinear Material Constants. J Nanomater 2017:1–15
24. Palani Kumar K, Keshavan D, Natarajan E et al (2021) Evaluation of mechanical properties of coconut flower cover fibre-reinforced polymer composites for industrial applications. Progress in Rubber, Plastics and Recycling Technology. 37(1):3–18. https://doi.org/10.1177/1477760619895011

Evaluation of Mechanical Properties of Woven Hybrid Reinforced Composites Fabricated by Vacuum Assisted Compression Molding Technique

B. Murali, B. Vijaya Ramnath, and K. Palanikumar

Abstract In this present research we aimed to detecting mechanical properties of Aloevera–Bamboo–Palm-Kevlar fiber reinforced composite materials. Among them three different combinational fabrication was performed (i) Type I (blend of aloevera and bamboo) (ii) Type II (blend of bamboo and palm) and (iii) Type III (blend of palm and aloevera). The mechanical characterization of naturally derived bio-composites was further analyzed. The Type-III strains showed higher strength as compared to other bio-composite fabrications in tensile (175 Mpa), flexural (253.96 Mpa), and hardness property (68 RHN). Similarly, the morphological characterization through SEM analysis displayed that in hybrid combinations adhesion between fibers and matrix was appropriate.

Keywords Kevlar fibre · Hybrid composites · Mechanical properties · SEM

1 Introduction

Biological and commercial chemical fibres was joined in the similar matrix to generate the composite hybrids that takes the most benefit of the significant content of the mixture compounds, and thus an ideal, greater but cheaper composite can be inclined [1]. In commercial-biological hybrid fibres composites, mostly investigation research drives to decrease the usage of chemical commercial fibres. Chief elements of a composites includes fibers and matrix which highly impact the operating mechanisms existing inside the composites throughout the let-down modes, loading, and impairment progression also mainly involved in the strength improvement. In general polymer composite depiction reinforced with Kevlar, carbon, glass and other natural fibers was investigated in the previous research [2]. The composite

B. Murali (✉)
Department of Mechanical Engineering, Vel Tech Rangarajan Dr, Sagunthala R&D Institute of Science and Technology, Avadi, Chennai 600062, India

B. V. Ramnath · K. Palanikumar
Department of Mechanical Engineering, Sri Sai Ram Engineering College, Chennai 600044, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_13

elements, including matrix and fibres, impact the working mechanism inside the composites through failure modes, loading, progressive damage, along with the composite strength. Generally, characterization of Jute-Flax Constructed Glass Fiber Reinforced Composite were investigated [3]. Despite there is less research which is highly focused on the Boron and Kevlar-49 thermosetting composite laminates properties which deliver commendable mechanical properties. Material selection and characterization in synthetic woven fabrics the hybridization have to be performed in a cautious method subsequently the materials of the composite with their specific range of usage and confines. Operative hybridization of fabric woven along with E glass, carbon, also the aramids including fibres belongs to Kevlar delivers significant way to describe the potential biological composites [4, 5]. Regular fibers have been utilized by people from early occasions. Lately, the usage of regular composite fibers was changed to suggestively rising consideration [6–16]. In a previous study, Ratna Prasad et al. [17] illustrated the diverse mechanical and physical properties of a flax fibre-reinforced concrete (FFRC) in the new and hardened state. In their study, they found that the effect of flax fibres in concrete has the impact of significantly decreasing its efficiency. Generally it was perceived that raising the strength of flexuralstrength was accompanied by reducing of compressive strength. Similarly, the natural fibres of mechanical assets of polymer reinforcement composites enormously rely upon singular assets of their parts also the inter-facial connection (bond) among hydrophobic matrix of polymer and reinforcement of hydrophilic nature [18]. Epoxy is multipurpose and built up with resin of thermoset holding epoxide collections since the agent in their unit with structure of poly-metric spine [19]. Fiber-based nominal composite polymer provides significant strength of mechanical also en-holds numerous benefits of interest over manufactured fiber on account of more significant accessibility, low thickness, high firmness, high level of adaptability, decreased vitality utilization, less wellbeing hazard, low abrasiveness. Regular fibers are biodegradable, minimal effort and great outcomes as far as exhibitions are a truly good fascination for the ventures [20–22]. Obviously not many investigations have been carried on the Kevlar with regular fiber epoxy reinforced composites to adjust its dynamic and mechanical portrayal things at the various proportions of framework. Along the lines the present examination was intended to identify the properties of mechanical fibre Aloe Vera–Bamboo–Palm-Kevlar fiber fortified composite materials through assisted vacuum resin transfer molding process. Thus, present results will be helpful to determine the impending applications of the natural composites and their manufacturing feasibility and more essentially reduces the chemical burden of our society.

Table 1 Physical nature of Aloe Vera, Palm, Bamboo, along with Kevlar fibers

Physical Nature	Aloevera	Bamboo	Palm	Kevlar
Density(g/cm^3)	1.3	0.5–1.2	1.46	1.42
Tensile strength (MPa)	298	142–232	273	936
Elastic modulus (GPa)	44	10–16	3.75	52
Elongation at break (%)	2.3	1.3	11.8	1.4

2 Experimental Details

2.1 Materials

In this, present investigation, Bamboo, Palm, Aloevera, and Kevlar fibers was utilized for composite specimen fabrication. Aloevera, Bamboo, Palm Fibers are in mat form and were attained from Jute Weaver Association Anakaputhur, Chennai, TamilNadu, India. Physical assets of Natural and Kevlar fibres are tabulated (Table 1). The Kevlar fiber, epoxy resin (LY-556) with density 1.25–1.22 g/cm^3, blended with hardener (HY-951) of density (0.97–0.99 g/cm^3) were procured from M/s Javanthee Traders, Chennai, Tamil Nadu, India.

2.2 Composites Fabrication

The specimen composite which consists of 5 layers with top fixed Kevlar fiber layers, middle also bottom specimen, respectively natural fibers includes Aloe Vera, Palm, and Bamboo fibers were packed in second and fourth layers. The fibres schedules for diverse composites were displayed in Table 2. For individual hybrid composite the matrix ratio to fiber were taken as 30:70, 40:60, 50:50 of composite sequence are displayed in Table 3. In this research, vacuum aided compression molding procedure is utilized, It is extremely dependable also productive over every added technique. In present method, downsides of diverse techniques are overwhelmed by making a vacuum inside the shape with the goal with air trap could not be framed intimate the composite. The different phases of this procedure presented (Fig. 1a–c). At

Table 2 Composite Laminates Sequence

(TYPE -I)	(TYPE -II)	(TYPE -III)
Kevlar	Kevlar	Kevlar
Aloevera	Bamboo	Palm
Kevlar	Kevlar	Kevlar
Bamboo	Palm	Aloevera
Kevlar	Kevlar	Kevlar

Table 3 Reinforcement/epoxy composites formulation

Composite samples	Epoxy resin (wt. %)	Reinforcement (wt.%)
S-1	70	30
S-2	60	40
S-3	50	50

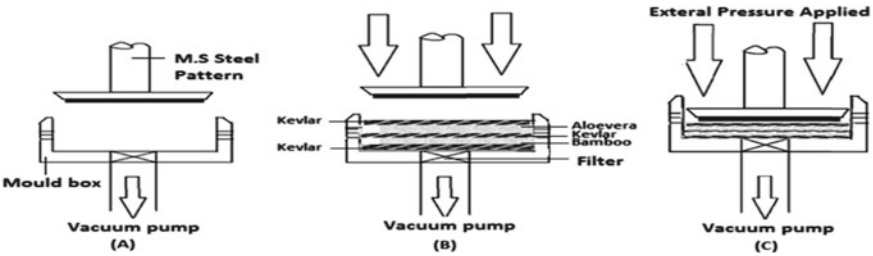


Fig. 1 Vacuum aided moulding of compression; Early stage of mold and design (**a**), Organization of fibers in mold (**b**), and Process of Compression (**c**)

first void, a shield was made intimate the shape confine by means of demonstrated (Fig. 1a). At that point, every one of the strands is set individually as appeared in Fig. 1b. At long last, the wood design through the froth was utilized in compacting the fiber layer displayed in Fig. 1c. Wake of framing the necessary blend, the shape was permitted to dry through a timeframe (5 h). Afterward manufactured overlay composite is launched out through the form. After the composite example gets solidified unpleasant edges are ejected and cut according to required measurements.

2.3 Mechanical Testing

Tensile properties were studied using universal testing machines. Load of tensile was higher while the stress amount practical on the laminate, which inclines to extend primarily, and then lastly it causes specimen breakage. The specimen responds towards the load is useful in any way axially inclined to the specimen breakage at specific phase. The tensile investigation is conceded out through the standard procedures of (ASTM D638). Fabricated composite laminate is blank as per the dimension specifications of tensile experiment in that way it relates as per the ideals [23]. Figure 2 Showed the ASTM standards for tensile tests to be carried out in sample composites.

Flexural test or III-point bending test were carried out by utilizing Universal Testing Machine (UTM). In flexural test, ability of specimen could tolerate the load under deformation. The chief requisite to perform flexural tests is to control its shear strength of inter-laminar where short beam shear investigations were executed.

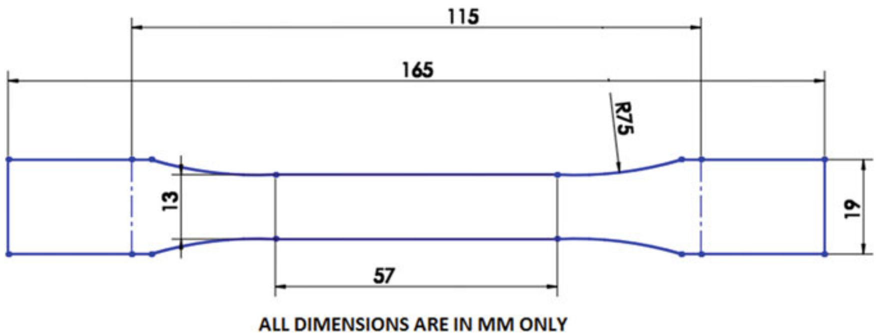


Fig. 2 Specimen of Tensile test [ASTM: D638]

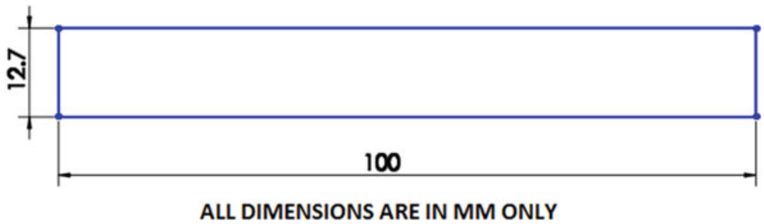


Fig. 3 Flexural test specimen [ASTM: D790]

Figure 3 shows the ASTM D790 standards for Flexural test to be carried out in the composite sample (Fig. 4).

The Hardness test primarily rests on the material assets of the projected ration inclines to grip impulsive shock which upshots in the testing the material hardness. The standard procedure of ASTM was cast-off for the (ASTM D2583) hardness assay.

3 Results and Discussion

3.1 Tensile Properties

The composite specimen I, II and III were evaluated for the tensile properties (Fig. 3a–c). The difference in their stress (Mpa) was displayed in the Fig. 3a. The results illustrate that in Type-I, S3 strains (Fiber 50% and Resin 50%) displayed significant tensile strength (93 Mpa) as compared to Type-I S1 and S2 samples respectively. Correspondingly, in Type-II natural composites, samples of S2 showed prominent tensile strength (107 Mpa) and it was statistically different as compared to Type-II S1 and S3 strains (Fig. 3b). Also, Type-III results displayed predominant tensile

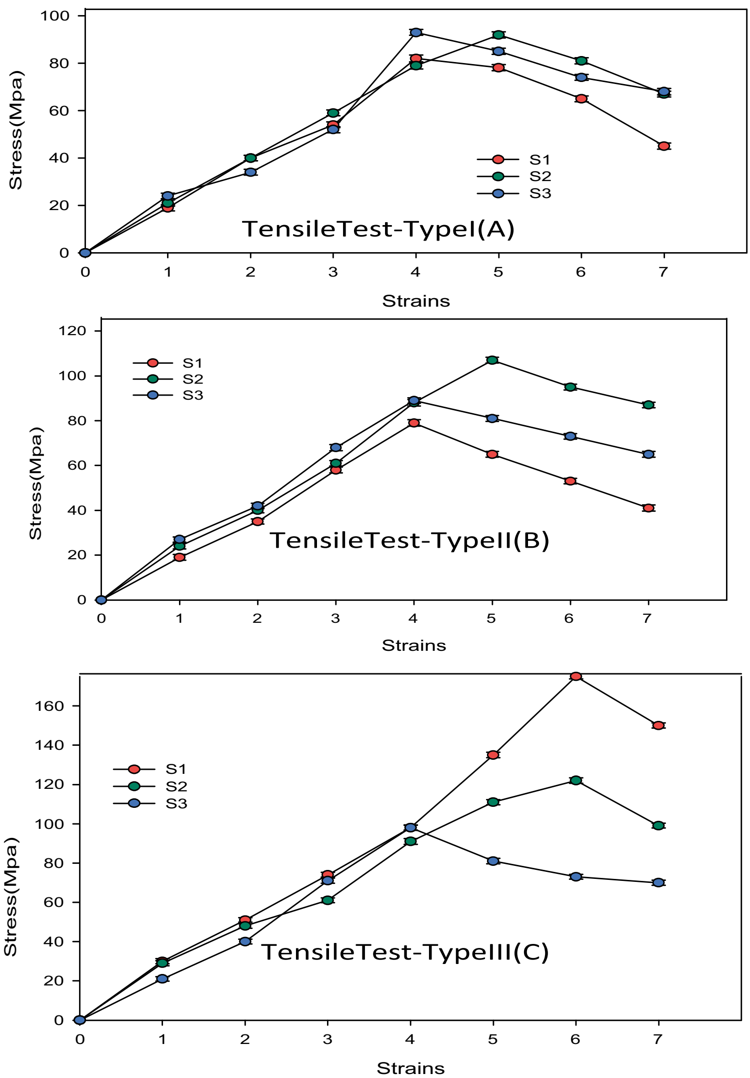


Fig. 4 Result of Tensile test

strength at S1 sample (175 Mpa) compared with S2 and S3 sample respectively (Fig. 3c). In all categories of composites includes I, II and III significant difference in the strength of tensile was detected between the samples. Also, the properties of tensile of the different specimens were tabulated in Table 4. In a comparative result of three categories, Type-III (S1) strains showed higher tensile properties as compared to other samples. Similarly, Ramnath et al. [24] showed that the fabrication and

Table 4 The properties of tensile in the different specimen

Composite	Break load (KN)	Displacement at break load (mm)	Elongation (%)	Ultimate tensile strength (MPa)	Tensile modulus (MPa)
(TYPE -I)					
S I	2.985	3.7	16.42	82	212.64
S II	3.83	4.6	16.65	92	238.52
S III	4.77	3.9	16.81	93	264.95
(TYPE -II)					
S I	3.59	3.8	14.02	79	221.87
S II	4.935	4.7	14.72	107	261.23
S III	4.62	4.8	14.43	89	289.54
(TYPE -III)					
S I	4.605	6.2	15.82	175	325.1
S II	5.49	6.5	15.34	122	299.62
S III	4.405	4.2	15.75	98	275.14

evaluation of Abaca and Jute fibers hybrid using glass fibres composites displayed 3 times higher tensile strength as compared to banana/sisal composite.

3.2 Flexural Properties

The different blends of materials of composite were experimented for its flexural unique properties through standard testing machines (Fig. 5a–c). The results displayed that in the Type-I category, S2 and S3 samples showed higher flexural strength compared to S1 strains. However, there is no significant difference between S2 and S3 samples. This illustrates that the strength of flexural of the composites upsurges when the hybrid composition of aloe vera and bamboo fibres increased with 40% and 50% of fibres in S2 and S3 samples respectively (Fig. 5a). Similar results were displayed in the Category II samples (Fig. 5). By comparing the ultimate flexural properties, III Category showed significant strength as compared to II and I. Thus, present results suggest that the alteration in fibre composition has significant flexural strength effects (Fig. 5c). The tensile properties of the diverse specimens were displayed in Table 5. Compared to our results, composites of hybrid banana and flax through a fraction volume of forty percentage utilizing Epoxy resin and Hardener (HY951). (GFRP) have better flexural strength than they are individually used [25].

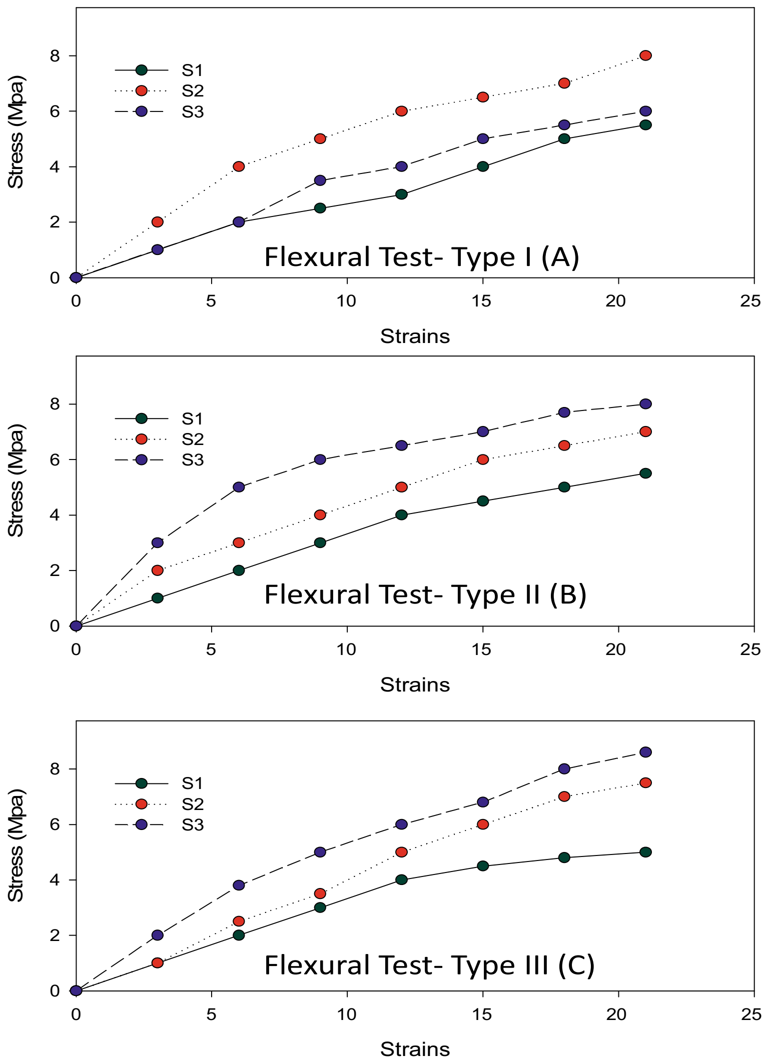


Fig. 5 Flexural test results of type i. II and III

3.3 Hardness

Rockwell hardness property of major three composite specimen results were displayed (Table 6). In general, hardness is chiefly influenced on the intended portion of the composites to absorb abrupt shock which upshots in testing of the hardness material. The Maximum hardness of composite samples were observed in type-I (S3-63 RHN), type-II (S2-64 RHN) and type-III (S1-68 RHN) respectively. All the samples were statistically different with one another. However, the maximum

Table 5 The different specimen flexural properties

Composite specimen	Break load (KN)	Displacement at break load (mm)	Elongation (%)	Ultimate flexural strength (MPa)
(TYPE -I)				
S I	0.195	14.7	9.76	166.77
S II	0.44	12.3	9.93	195.13
S III	0.465	20.8	9.81	176.26
(TYPE -II)				
S I	0.27	12.5	9.12	135.66
S II	0.405	14.8	9.54	196.3
S III	0.445	10.2	8.65	165.45
(TYPE -III)				
S I	0.175	20.7	10.02	253.96
S II	0.605	18.3	10.34	221.14
S III	0.595	17.8	9.76	207.84

Table 6 Hardness properties of the different specimen

Composite specimen	Hardness (RHN)
(TYPE -I)	
S1	59
S2	58
S3	63
(TYPE -II)	
S1	56
S2	68
S3	61
(TYPE -III)	
S1	62
S2	65
S3	67

hardness of the bio-composite was observed in type-III as compared to other two categories (Fig. 6). Our results were well supported with the previous statement that the percentage of the composite mixtures increase the stiffness of the individual composites [26, 27].

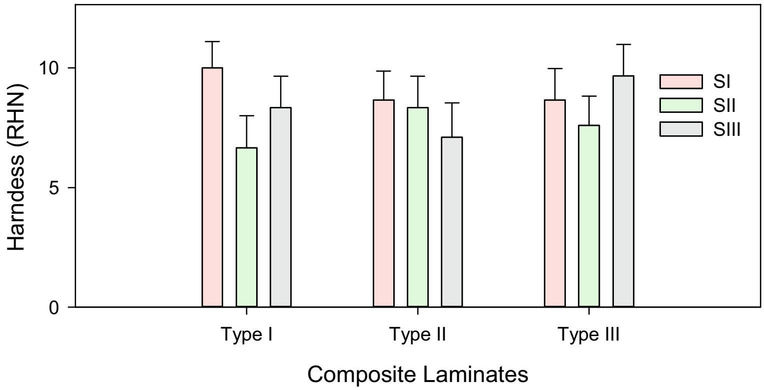


Fig. 6 Hardness test results of type I, II and III composite laminates

3.4 Morphological Examination Using Scanning Electron Microscope (SEM)

The analysis of morphological changes through SEM in bio-composite materials is executed and displayed (Fig. 7, 8 and 9). The samples from tensile tests of different composite types (Type I, II & III) were characterized. The surface specific breakage of fibre was displayed post tensile tested type-I sample (Fig. 7). Moreover, the SEM

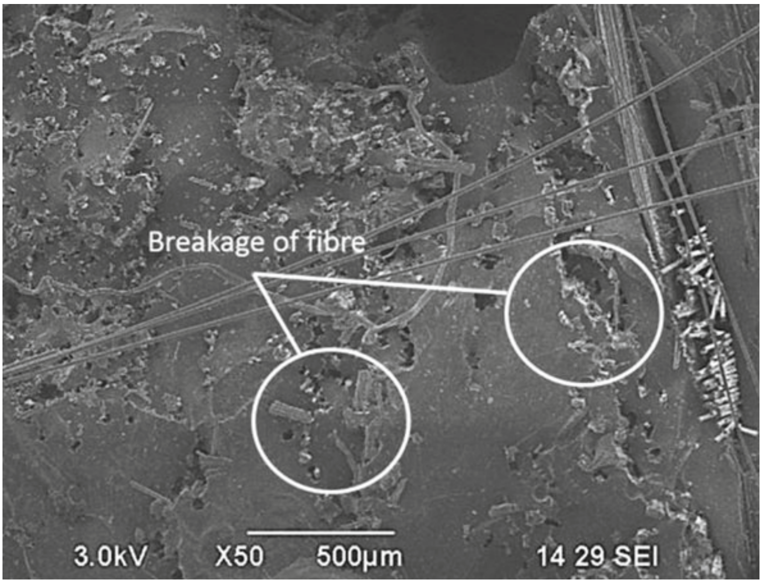


Fig. 7 Scanning Electron Microscope (SEM) analysis of Tensile tested type-I specimen

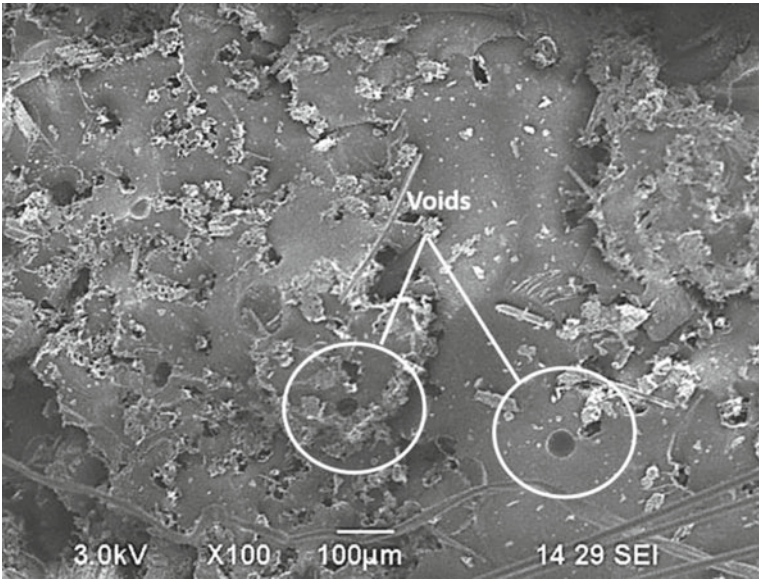


Fig. 8 Scanning Electron Microscope (SEM) analysis of Tensile tested type-II specimen

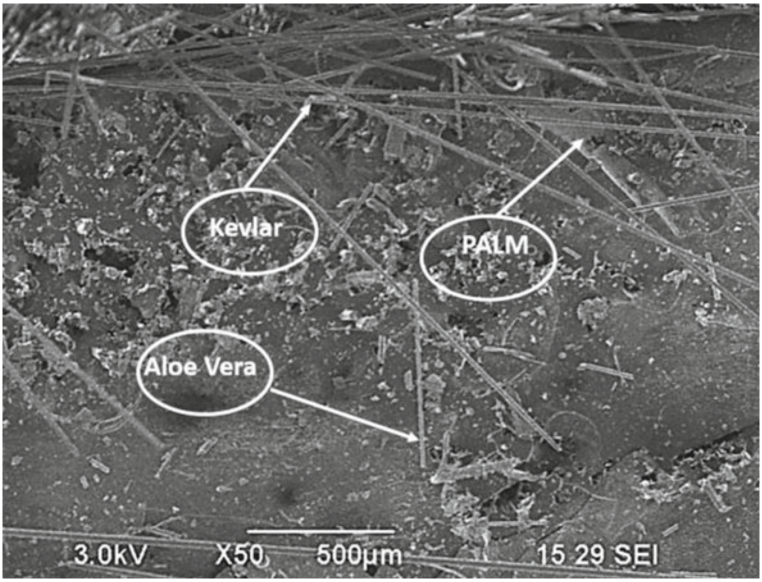


Fig. 9 Scanning Electron Microscope (SEM) analysis of Tensile tested type-III specimen

imageries were reserved to perceive the cracks exists in the internal part, Voids, interfacial assets and more importantly core assembly of composite materials surface fractured (Fig. 8). The individual bio composite fibre matrix (Kevlar, Palm and Aloe Vera) internal assembly were clearly presented in the (Fig. 9).

4 Conclusion

As an endnote, the present investigation displayed the fabrication process of three natural bio-composites derived from aloevera, bamboo, palm and kevlar fibers. Among them three different combinational fabrication was performed (i) Type I (blend of aloe vera and bamboo) (ii) Type II (blend of bamboo and palm) and (iii) Type III (blend of palm and aloevera). The tensile, flexural, and hardness property results revealed that the Type-III strains showed higher strength as compared to other bio-composite fabrications. Overall, the present research suggests that the bio-composites blend of palm and aloevera showed enhanced mechanical assets as related to added natural-fabrications. Thus, the bio-rational plants will be helpful to determine the impending uses of the natural composites and their feasibility of manufacturing in different industrial sectors.

References

1. Elanchezhian C, Vijaya Ramnath B, Ramakrishnan G, Rajendrakumar M, Naveenkumar V, Saravanakumar MK (2018) Review on mechanical properties of natural fiber composites. Mater Today-Proc. 5:1785–1790
2. Joshi SV, Drzal LT, Mohanty AK, Arora S (2004) Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos Part A Appl Sci Manuf 35:371–376
3. Vijaya Ramnath B, Elanchezhian C, Nirmal PV, Prem Kumar G, Santhosh Kumar V, Karthick S, Rajesh S, Suresh K (2014) Experimental Investigation of Mechanical behavior of Jute-Flax Based Glass Fiber Reinforced Composite. Fibers Polym. 15:1251–1262
4. Vijaya Ramnath B, Manickavasagam VM, Elanchezhian C, Vinodh Krishna C, Karthik S, Saravanan K (2014) Determination of mechanical properties of intra-layer abaca–jute–glass fiber reinforced composite. Mater Des 60:643–652
5. Reddy AC (2015) Evaluation of curing process for Kevlar 49-epoxy composites by mechanical characterization designed for brake liners. Int J Sci Res 4:2365–2371
6. Razak NIA, Ibrahim NA, Zainuddin N, Rayung M, Saad WZ (2014) The influence of chemical surface modification of kenaf fiber using hydrogen peroxide on the mechanical properties of biodegradable kenaf fiber/poly(Lactic Acid) composites. Molecules 19:2957–2968
7. Yousif BF, Shalwan A, Chin CW, Ming KC (2012) Flexural properties of treated and untreated kenaf/epoxy composites. Mater Des 40:378–385
8. Sharba MJ, Leman Z, Sultan MTH, Ishak MR, AzmahHanimMA. Effects of kenaf fiber orientation on mechanical properties and fatigue life of glass/kenaf hybrid composites.BioResources. 2016; 11:1448–1465.
9. Yusoff RB, Takagi H, Nakagaito AN (2016) Tensile and flexural properties of polylactic acid-based hybrid green composites reinforced by kenaf, bamboo and coir fibers. Ind Crops Prod 94:562–573

10. Yahaya R, Sapuan SM, Jawaid M, Leman Z, ZainudinES.Effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf-aramid hybrid laminated composites. Mater Des. 2015; 67:173–179
11. Khan JA, Khan MA (2014) The use of jute fibers as reinforcements in composites. Bio fiber Reinf Compos Mater. 3:1342–1352
12. Asim M, Jawaid M, Abdan K, Ishak MR (2018) The effect of silanetreatedfibre loading on mechanical properties of pineapple leaf/kenaf fibre filler phenolic composites. J Polym Environ 26:1520–1527
13. Sivakumar D, Ng LF, Lau SM, Lim KT (2018) Fatigue life behaviour of glass/kenaf woven-ply polymer hybrid bio composites. JPolym Environ. 26:499–507
14. Jawaid M, Khalil HPSA, Bakar AA (2011) Hybrid composites of oil palm empty fruit bunches/woven jute fiber: chemical resistance, physical, and impact properties. J Compos Mater 45:2515–2522
15. Yahaya R, Sapuan S, Jawaid M, Leman Z (2014) Zainudin Mechanical performance of woven kenaf-Kevlar hybrid composites. J ReinfPlast Compos. 33:2242–2254
16. Murali B, Vijaya Ramnath B (2019) Mechanical Properties of Boehmeria Nivea Reinforced Polymer Composite. Materials Today: Proceedings 16:883–888
17. Ratna-Prasad AV, Mohanarao K (2011) Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo. Mater Des 32:4658–4663
18. Sepe R, Bollino F, Boccarusso L, Caputo F (2018) Influence of chemical treatments on mechanical properties of hemp fiber reinforced composites. Compos Part B Eng 133:210–217
19. Saba N, Safwan A, Sanyang M, Mohammad F, Pervaiz M, Jawaid M et al (2017) Thermal and dynamic mechanical properties of cellulose nanofibers reinforced epoxy composites. Int J Biol Macromol 102:822–828
20. Patel VK, Chauhan S, Katiyar J. Physico-mechanical and wear properties of novel sustainable sour weed fiber reinforced polyester composites. Mater Res Express. 2018; 5(4):045310.
21. Kumar S, Gangil B, Patel VK. Physico-mechanical and tribological properties of grewiaoptiva fiber/bio-particulates hybrid polymer composites. AIP Conf Proc.2016; 1728(1):020384
22. Murali B, VijayaRamnath B (2021) DhanashekarM. Chandramohan Experimental Investigation on stacking Sequence of Kevlar and Natural Fibres/Epoxy Polymer Composites, Polimeros: Ciencia e Tecnologia 31:1–9
23. Raja RN, Kokan SJ, Narayanan RS, Rajesh S, Manickavasagam VM, Vijaya RB (2013) Fabrication and testing of abaca fibre reinforced epoxy composites for automotive applications. Adv Mater Res 718:63–68
24. Vijaya Ramnath B, Junaid Kokan S, Niranjan Raja R, Sathyanarayanan R, Elanchezhian C, Rajendra Prasad A, Manickavasagam VM (2013) Evaluation of mechanical properties of abaca–jute–glass fibre reinforced epoxy composite. Mater Des 51:357–366
25. Srinivasan VS, Boopathy SR, Sangeetha D, Vijaya RB (2014) Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite. Mater Des 60:620–627
26. Haque M, Hasan M, Islam S, Ali E (2009) Physico-mechanical properties of chemically treated palm and coir fiber reinforced polypropylene composites. Bio resource Technol. 100:4903–4906
27. Shanmugam D, Thiruchitrambalam M (2013) Static and dynamic mechanical properties of alkali treated unidirectional continuous Palmyra Palm Leaf Stalk Fiber/jute fiber reinforced hybrid polyester composites. Mater Des 50:533–542

Influence of Fiber Content on Tensile and Flexural Properties of Ramie/Areca Fiber Composite—Ān Algorithmic Approach Using Firefly Algorithm

D. Vijayan and T. Rajmohan

Abstract Natural Fiber-Reinforced Composites (NFRC) are owing to their decomposability, biodegradability, and cost-efficient. They can be used as a reinforced material with natural/synthetic resins to formulate a composite material for various applications. The present work investigates the influence of fiber content of fabricated ramie/areca natural fiber composite on tensile and flexural strength by varying their fabricating process parameters, namely alkali concentration, curing temperature, and compression pressure. A scanning electron microscope was used to assess the mechanical and metallurgical properties of the fabricated hybrid composite. Results revealed that the quality of bonding and defects characteristics of the fractured surfaces of the composite. Furthermore, a regression model was developed for each response, such as tensile and flexural strength, to introduce an evolutionary algorithm, namely the Firefly algorithm, to find optimal settings of processing parameters of the composite. Further, the algorithmic results were validated with experimental results to check the adequacy of the model. The results revealed that the obtained optimal processing parameters close to the experimental values confirm adequacy and yield the maximum tensile and flexural strength of 76.25 and 136.36 MPa.

Keywords Ramie · Areca · Firefly · Evolutionary · Metaheuristic · Algorithm · Optimization · Natural fiber · Composite · Influence · Tensile · Flexural · Mechanical

1 Introduction

Nowadays, NFRC has many mechanical engineering applications, including sports cars, high-speed rail, and resistance systems [1, 2]. Composites made up of natural fibers are highly tensile and compressive and the best modulus of elasticity. Compared to polymer composites, natural composites are supplemented with additional binder

D. Vijayan (✉) · T. Rajmohan
Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya (SCSVMV) University, Kanchipuram 631561, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_14

materials such as silicon carbide, carbon nanoparticles, nano-silica, and fly ash [3–5]. However, the properties of natural fiber composites depend on many crucial elements, such as the ratio of resin and fiber, the quality of the fiber material, the compression pressure, and the compression time [6]. Therefore, predicting their mechanical properties is essential because it can aid in planning operations in the early stages of product design that give precise product requirements. Also, the best approach for estimating the mechanical properties of NFRC helps us save time and costs during the product development stage itself. However, many material's mechanical properties are non-linearly conflicting in nature example, tensile and compressing properties. Therefore, attaining a solution by traditional optimization approaches may not be possible, and it takes more time to find the solution [7, 8]. The research community has proposed many approaches whenever conflicting objective arises during product development. For instance., Sultana et al. [9] applied a crow search evolutionary algorithm to optimize the process parameters of jute fibers. The authors found that overall predicted values varied 5% compared to experimental values, and they have concluded that the evolutionary algorithms are powerful in predicting the optimal values of natural fibers from the experimental results.

Hu et al. [10] proposed an improved direct simulated annealing algorithm (IDSA) for simultaneous optimization design to determine fiber orientation and topology. They identified that IDSA has optimizing parameters accurately as similar to other optimization techniques. Savran et al. [11] have proposed the stochastic optimization method for finding the stacking sequence of carbon/epoxy-sitka spruce hybrid composite. The authors found that the tensile properties improve when fabricated with obtained optimal stacking sequence as suggested by the optimization algorithm. These findings conclude the optimization has necessary in all areas of the human venture, from genetic cells to rocket sciences, vacations and agricultural production development, working hours, and much more.

Optimization algorithms are looking for a vector that provides a better solution to a particular problem. There are two main classes of optimization algorithms, namely, deterministic and stochastic optimization algorithm. If the search process starts from the same start, a determining method narrows the solution to the same point. Similarly, approximate optimization methods provide some randomness and deliver different solutions; there are two types of stochastic algorithms: heuristic and metaheuristic [12]. Heuristic methods solve the problem through error-free experiments and methods. These algorithms do not guarantee that to get reasonable solutions all the time. We can rely on heuristic algorithms when the goal is to find an excellent solution to time constraints and available information. A set of rules governs metaheuristic algorithms that combine both local search and randomness. Also, these provide more flexibility in finding global minima than capturing local minima; population-based meta-heuristic optimization algorithms find the solution from various primary solutions rather than single solutions, encouraging the search area naturally to explore significant potential compared to meteorological methods. For example, a genetic algorithm (GA) is designed naturally by biological evolution; particle swarm optimization (PSO) simulated the flock social behaviors.

2 Fabrication of Composite

Ramie/Areca fibers, epoxy resin (Araldite LY556), and the desired hardener (grade: HY951) collected from M/s. Green composites, Chennai. By weight percentage, epoxy resin and hardener is mixed in a separate beaker. Since the matrix may lose its mechanical strength due to bubbles, hence the solution stirred carefully. Each composite sample has prepared by using the compression molding machine. The sample has made for 30 cm x 30 × cm sizes, having seven layers and following the ARARARA stacking sequence. The top and bottom layers are laid up by areca, whereas ramie fiber layers are considered intermediate in each sample. The fabricated sample of ARARARA is as presented in Fig. 1. The Box-Behenken Design (BBD) based RSM design proposed to organize each experiment systematically. Four crucial processing parameters, namely Alkali Concentration (AC), Fiber Content (FC), Curing Temperature (CT), and Compression Pressure(CP). There are three levels considered for each parameter, i.e., −1,0 and + 1. Table 1 shows processing parameters and their levels of the present investigation, and Table 2 shows the design variables and their responses, namely tensile strength (TS) and flexural strength (FS).

Fig. 1 Fabricated ARARARA composite sample

Table 1 Process parameters and their levels

Symbol	Processing parameters	Units	-1	0	1
X(1)	Alkali concentration	%	3	6	9
X(2)	Fiber Content	%	30	40	50
X(3)	Curing Temperature	Deg	60	80	100
X(4)	Compression Pressure	Bar	60	80	100

Table 2 Design matrix and their responses

S No	X(1) (%)	X(2) (%)	X(3) (^{O}C)	X(4) (bar)	TS (MPa)	FS (MPa)
1	3	30	80	80	65.862	119.227
2	9	30	80	80	71.662	124.279
3	3	50	80	80	72.669	119.106
4	9	50	80	80	75.550	121.922
5	6	40	60	60	75.392	125.442
6	6	40	100	60	75.000	129.799
7	6	40	60	100	72.226	110.275
8	6	40	100	100	73.295	108.310
9	3	40	80	60	72.546	135.312
10	9	40	80	60	64.108	124.889
11	3	40	80	100	73.313	106.508
12	9	40	80	100	68.267	96.852
13	6	30	60	80	72.612	111.783
14	6	50	60	80	75.451	112.974
15	6	30	100	80	71.165	123.035
16	6	50	100	80	74.745	110.576
17	3	40	60	80	72.704	121.326
18	9	40	60	80	72.993	110.446
19	3	40	100	80	72.656	112.864
20	9	40	100	80	71.328	122.631
21	6	30	80	60	69.198	135.871
22	6	50	80	60	74.197	131.414
23	6	30	80	100	70.639	94.561
24	6	50	80	100	74.040	107.059
25	6	40	80	80	72.535	110.985
26	6	40	80	80	74.794	112.593
27	6	40	80	80	72.224	123.742
28	6	40	80	80	71.820	124.819
29	6	40	80	80	71.150	123.483

3 Firefly Algorithm

A novel Firefly Algorithm (FA) developed by Yung [13] is proposed in the present investigation. FA is used for solving multi-response optimization, especially for simultaneous objective optimization problems by simulating the social behavior of fireflies. FA has improved from its basic versions through many variations by researchers in recent days. The FA showed its superiority in finding optimal parameters over other similar evolutionary algorithms such as artificial bee colony (ABC), particle mass optimization (PSO), and genetic algorithm (GA) [13].

Three idealized rules in FA: (1) fireflies are of both sexes, i.e., they are attracted to other fireflies irrespective of their gender; (ii) The attractiveness of fireflies is proportional to their brightness; therefore, the brightest will go to the brightest. Attractiveness and brightness is increase when distance increase. Randomly move when no firefly is brighter than another firefly; (3) the target function determines each firefly's glow [14, 15]. The flow chart of the FA is as presented in Fig. 2. The brightness can be proportional to the value of the objective function for the maximization problem and the inverse of the minimization problem. The firefly population of each represents a candidate solution. Let $X = (x_1, x_2, \ldots x_N)$ be the firefly population, where $x_i^1 = (x_i^1, x_i^2, \ldots, x_i^D)$ is the ith firefly, N is the size of the population and D is the dimension. For any two different fireflies x_i and x_i and $x_j (i \neq j)$, The expression of attractiveness represented below,

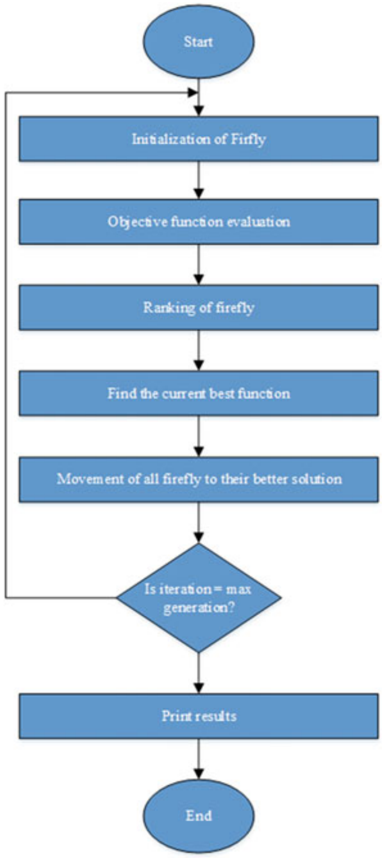


Fig. 2 Firefly algorithm flowchart

$$\beta = \beta_0 e^{-\gamma r^2}$$

The light absorption coefficient is γ; if the $\gamma = 0$, the firefly's attraction distance does not change; if $\gamma \rightarrow \infty$, The fireflies are no longer attracted to each other. Therefore γ varies between 0.1 to 10 in regular exercise.

x_i and x_j are the distances represented as r_{ij}, and it can be expressed as follows [16]

$$r_{ij} = \sqrt{\sum_{k=1}^{d} \left(x_i^d - x_j^d\right)^2}$$

and then the firefly position (x_i) will be updated to

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} \left(x_j - x_i\right) + \alpha \in_i$$

In the above expression $\in_i$, usually, it varies in the range of 0 to 1. In addition, α indicates the step factor. Sometimes fireflies make a simple random walk; therefore it is represented as β_0, and the value lies between 0 and 1.

4 Results and Discussion

Figure 3a–c shows the influence of fiber content, alkali concentration, curing temperature, and compression pressure on the responses such as tensile and flexural strength.

4.1 Influence of Fiber Content Versus Alkali Concentration on Tensile Strength

Figure 3a depicts 3D response surface plot of fiber content (areca and ramie fibers) versus alkali concentration on tensile strength. It can understand that less fiber content produced low tensile strength. Since less fiber content of both ramie and areca fibers allows free resin flow between the fiber layers. Therefore, the matrix failed to transfer the applied load along the fibrils caused pinholes on the laminated surfaces, as revealed in Fig. 3b. Hence, TS is low (62.54 MPa) when fiber content is low. The nature of areca and ramie fibers allows the epoxy resin along the pores of fiber layers to have better wettability, as shown in Fig. 3. Thus TS is high (76.25 MPa) when the fiber content is high. The obtained TS value is 55.28% higher, indicating the tensile strength of the laminated composite increase when increasing fiber content. Moreover, the alkali solution treatment slightly increases the tensile strength up to

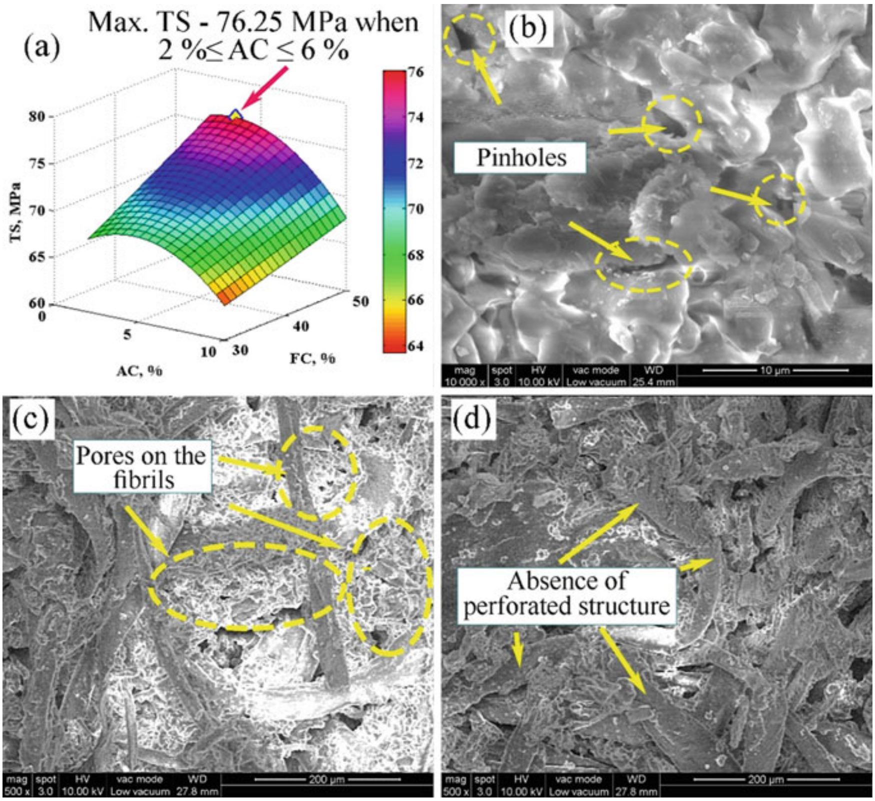


Fig. 3 **a** 3D surface plot of fiber content versus percentage of alkali concentration on tensile strength, **b**. pinholes on the laminated surface, **c**. Pores on the fibrils, **d** Absence of perforated structure on the laminated areca and ramie fibers

3.5% by increasing alkali concentrate from 2 to 6% and then decreased up to 2% when increased concentrate from 6 to 10%.

An increase in the percentage of alkali solution from 2 to 6% produces a coarser surface within the fiber structure that increases the interfacial adhesion between the fiber and matrix. Whereas increasing beyond 6% of alkali solution, the adhesion between fibrils decreases due to excessive removal of lignin, hemicellulose, and other natural impurities from the fiber layers decrease the degree of surface roughness on the fiber layers [17]. And the absence of a perforated structure on fibers called 'trichomes' failed to enhance the mechanical bonding due to the high concentrate of alkali solution, as exposed in Fig. 3d. Hence low tensile strength was achieved on the laminated composite beyond 6% of alkali solution treatment. MohanDas et al. [8] observed similar effects while evaluating the mechanical properties of fine areca fiber reinforced phenol formaldehyde composite.

4.2 Influence of Fiber Content Versus During Temperature on Tensile Strength

Figure 4a depicts the 3D response surface plot of fiber content influence, curing temperature on TS of areca/ ramie fibers composite. The samples with more fiber content that cured with 60OC temperature produced high TS (76.25 MPa). When the sample cured between 80 to 100 °C, delivering low tensile strength. High curing temperature failed to increase the TS beyond 76.25 MPa even though fiber content is low/high. Relatively high curing temperature creating more voids and pits on the composite surfaces, as shown in Fig. 4b.

Moreover, the high temperature enhanced the fiber degradation and swelling rate on the laminated surfaces and missing to retain a substantial amount of hemicellulose and other impurities within the matrix, as seen in Fig. 4c. Hence TS is drastically

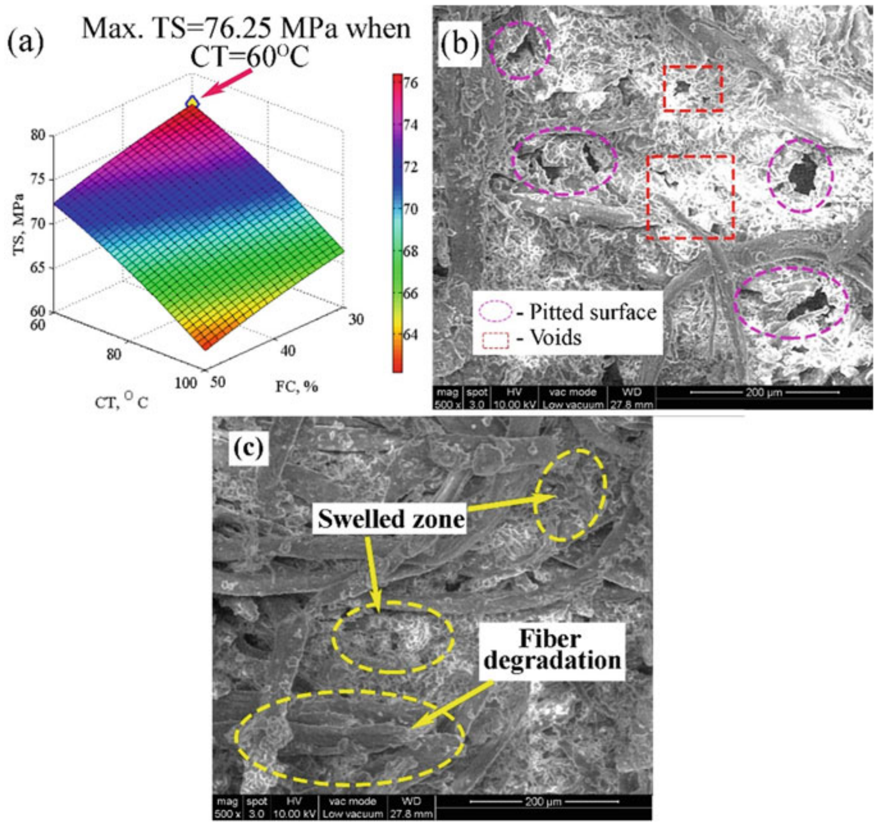


Fig. 4 **a** 3D surface plot of fiber content versus curing temperature on tensile strength, **b** Pitted surface and voids on the laminated surface, **c** swelled zone and fiber degradation on the laminated areca and ramie fibers

reduced when composite fabricated with high temperature. Habibi et al. [18] and Jaafar et al. [19] reported similar observations during the fabrication of pineapple and flax natural fibers.

4.3 *Influence of Fiber Content Versus Compressive Pressure on Tensile Strength*

Compressive pressure is another dominating factor in the fabrication of natural fiber composite using the compression molding process. Figure 5a depicts the fiber content effect and compressive pressure on tensile strength. Enhancement of bonding strength between fiber and matrix increases the TS when increasing compressive pressure at low fiber content (30%). The fibers were allowed the resin flows along the length of each fiber. Therefore an excellent interfacial bonding was obtained on the laminated composite with an accumulated pressure, as shown in Fig. 5b.

Hence TS of the laminated composite increased though the fiber content is low. However, further, increase of compressive pressure beyond 80 MPa significantly when the fiber content above 30%, tensile strength decreased due to an adverse effect on the mechanical properties such as fiber and matrix breakage as shown in Fig. 5c. High compression pressure (80 bar $\leq$ CP $\leq$ 100 bar) induced a non-uniform stress distribution on the fiber and matrix that provided better compaction. Increasing fiber content beyond 30% indirectly increases fiber density, restricting the free flow of resin between the fibers. The dense fibers restrict the resin flow, thus prevents better chemical bonding between the fibers and matrix. Subsequently, the combination of temperature and pressure lead to cut the long fiber, which enabled porosity and voids on the composite, as shown in Fig. 5d. Hence, there is a variation in TS (80 bar $\leq$ CP $\leq$ 100 bar) on the composite surfaces when increasing compressive pressure. Soundhar, Kandasamy [20], and Tomo et al. [21] revealed similar observations on the fabrication of sisal and kenaf natural fibers composites.

4.4 *Influence of Fiber Content Versus Alkali Concentration on Flexural Strength*

Figure 6a shows the fiber content influence and alkali concentration on the flexural strength of ramie/areca composite. The composite FS increases with increasing alkali concentration from 3 to 5% irrespective of fiber content.

Since increasing alkali concentration could break the large fiber bundles into smaller fibrils, thus allowed the resins freely. Moreover, increasing alkali concentration exposed more hemicellulose, lignin, and other impurities. Hence an excellent bonding strength on the fiber's produced high FS on the composite, as presented in

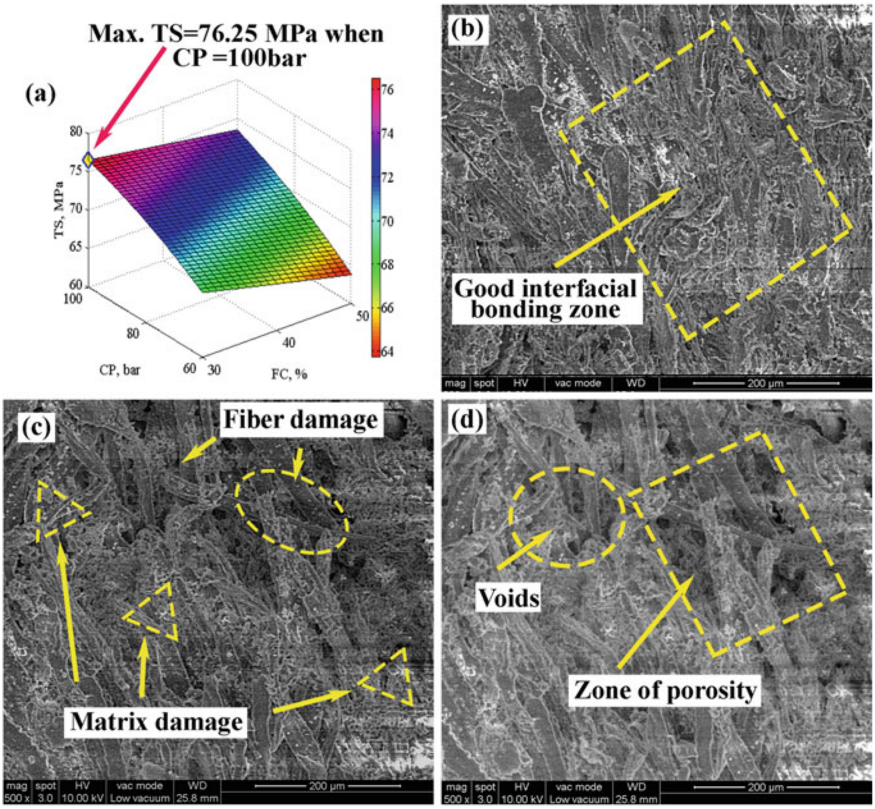


Fig. 5 **a** 3D surface plot of fiber content versus compression pressure on tensile strength, **b** Interfacial bonding zone, **c** Fiber and matrix damage on the laminated surface, **d** Zone of porosity and voids

Fig. 6b. The composite achieved the maximum FS of 136.36 MPa. It can be understood from the results that the alkali treatment more positive impacts on enhancing FS compared to the TS of the composite. Costa et al. [22], Ozerkan et al. [23], and Chowdhury et al. [24] reported similar findings on the surface treatment analysis of palm, Pinus Elliottii, and basalt natural fibers. However, increasing alkali concentration beyond 5% more portions of hemicellulose, lignin came out, thus reduce the fiber geometry; as a result, both areca and ramie fibers have shown low FS. When increasing the alkali concentration beyond 5%, achieved a maximum FS of 96.37 MPa. The obtained FS has 29.32% less, which indicates that above 5% of alkali concentration is not suitable for the treatment of ramie and areca fibers and decreases the flexural strength of the laminated composite. Moreover, excess alkali concentration solution created a slight discontinuity between the fibers, as shown in Fig. 6c. Similar observations were found by Bharathiraja et al. [25] and Banagar et al. [26] on the mechanical characterization of coir fiber and areca sheath fiber composites.

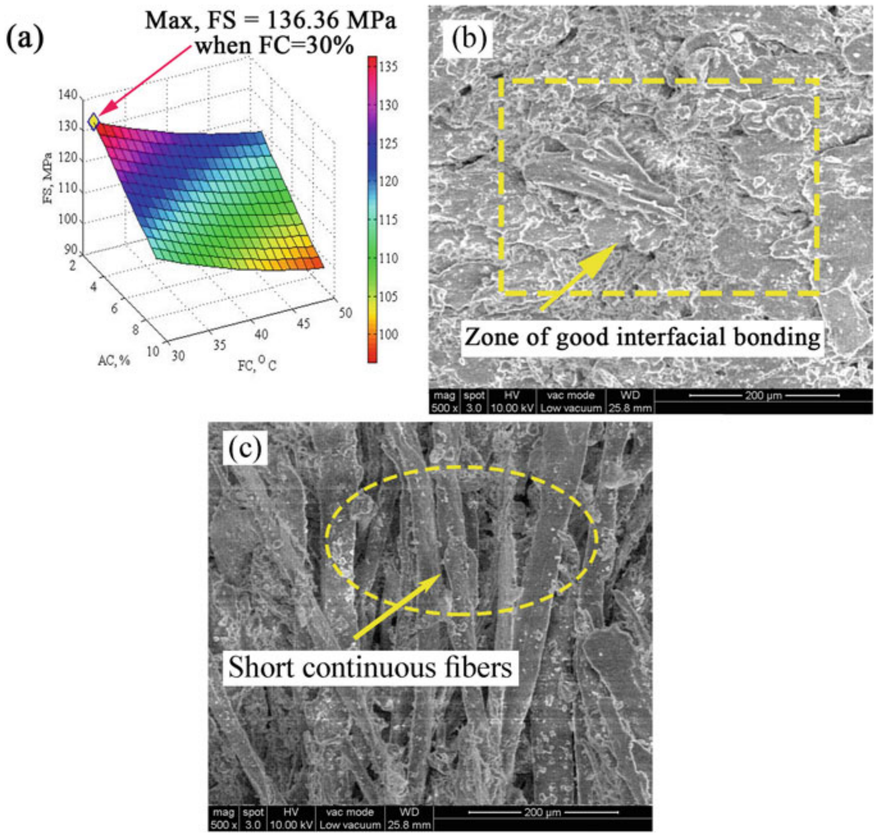


Fig. 6 **a** 3D surface plot of alkali concentration versus fiber content on flexural strength, **b** Zone of interfacial bonding, **c** Short continuous fibers

4.5 Influence of Fiber Content Versus Curing Temperature on Flexural Strength

Figure 7a shows the 3D surface plot of the fiber content influence and curing temperature on the FS of ramie/areca composite. It is understood that increasing curing temperature from 60 to 80OC increases the composite's FS. Increasing beyond 80OC (80OC $\leq$ CT $\geq$ 100OC) decreases the FS due to excess fiber burnout, as shown in Fig. 7b. And this fiber burnout can be observed even the composite has fabricated with high fiber content. Hence, when the composite cured between 80 to 100OC temperature, low FS is observed and yielded the maximum FS of 96.37 MPa.

For good flexural strength, adequate interfacial bonding strength is necessary. Due to excess curing temperature, an amount of supplied heat burns the laminated fibers and thus leads to poor interfacial bonding. Hence low flexural strength was observed on the fabricated composite [27, 28]. The overall obtained result shows that the

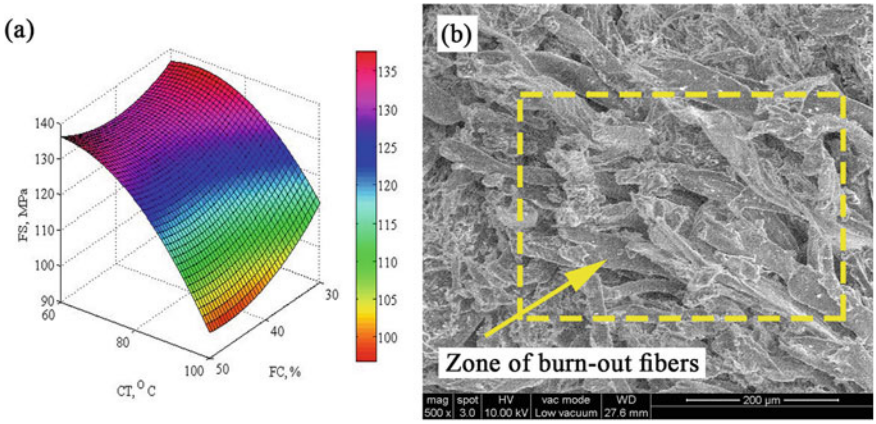


Fig. 7 **a** 3D surface plot of curing temperature versus fiber content on flexural strength, **b** Zone of burnout fibers

curing temperature levels between 60 to 80OC are affordable to produce maximum flexural strength on the fabricated ramie/areca fiber composite. These findings are in line with those in the study reported Singh et al. [29], Bajpai et al. [30]

4.6 Influence of Fiber Content Versus Compression Pressure on Flexural Strength

Figure 8a shows a 3D surface plot of the fiber content influence and compressive pressure on flexural strength. Increasing compressive pressure from 60 to 100 bar (60 bar $\leq$ CP $\geq$ 100 bar) increases FS irrespective of low/high fiber content. The result findings show that the compression pressure has the most significant parameter for increasing the flexural strength of the ramie/areca composites.

This phenomenon indicates that the fabricated ramie/areca fiber composite exhibits considerable bonding between the fibers. However, due to low fiber content (FC = 30%), numerous voids and dimples are observed on the fractured surfaces, as shown in Fig. 8b. In contrast, when increasing compression pressure beyond 80 bar $\leq$ CP $\geq$ 100 bar, the voids present in the composite surface have reduced, and subsequently, the composites' density increased when fiber content is high. Therefore better interfacial bonding was observed on the composite, as shown in Fig. 8c.

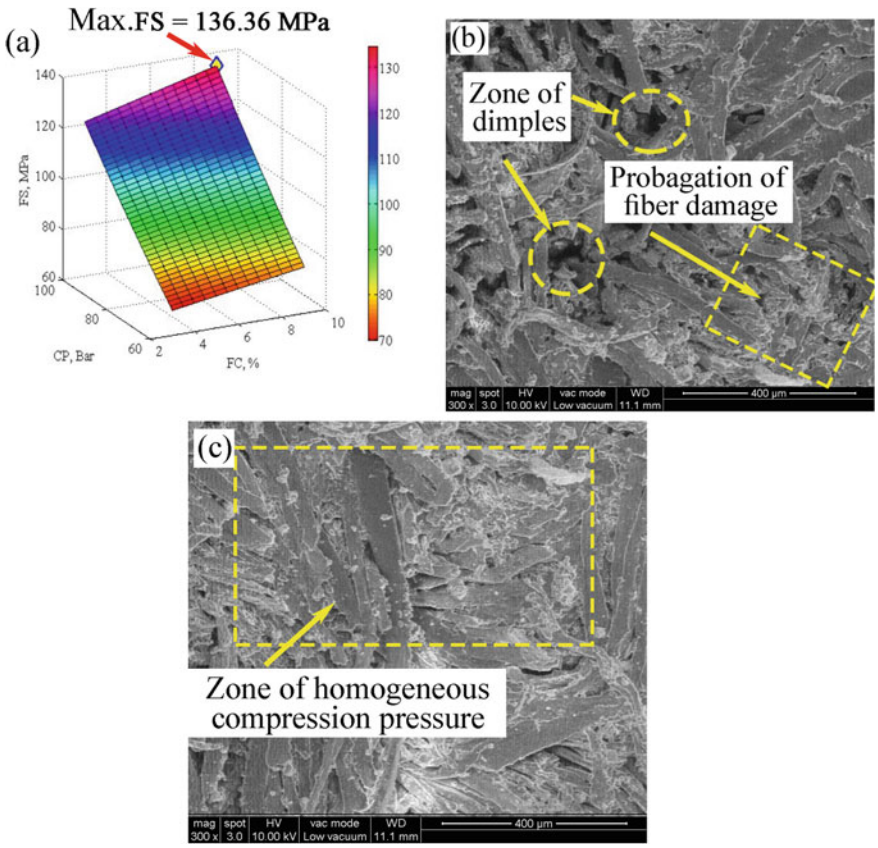


Fig. 8 **a** 3D surface plot of fiber content versus compression pressure on flexural strength, **b** zone of dimples, **c** Zone of homogeneous compression pressure

5 Optimization of Parameters Using Firefly Algorithm

5.1 Development of a Mathematical Model

Multi-objective optimization has been applied in the present investigation to obtain optimal fabricating parameters using the Matlab program. Therefore, to create a multi-objective regression model, the regression equations are developed using the response surface method for each TS and FS. The developed regression equations are given below,

$$
\begin{aligned}
TS = & +16.474 + 0.438 \times X(1) - 0.415 \times X(2) + 0.505 \times X(3) \\
& +0.956 \times X(4) + 1.351e^{-4} \times X(1) \times X(2) + 9.431e^{-3} \times X(2) \times X(3) \\
& -7.912e^{-3} \times X(3) \times X(4) - 0.0107 \times X(2) \times X(3) \\
& +6.714e^{-3} \times X(2) \times X(4) - 6.706e^{-3} \times X(3) \times X(4) - 3.984e^{-3} \times X(1)^2 \\
& +7.116e^{-3} \times X(2)^2 + 1.964e^{-4} \times X(3)^2 - 2.909e^{-3} \times X(4)^2
\end{aligned}
$$

$$
\begin{aligned}
FS = & +457.8 + 0.66406 \times X(1) - 6.04918 \times X(2) \\
& +1.505 \times X(3) + 3.767 \times X(4) - 0.017502 \times X(1) \times X(2) \\
& +5.3275e^{-3} \times X(1) \times X(3) + 0.0793 \times X(1) \times X(4) \\
& -0.0249 \times X(2) \times X(3) - 0.027 \times X(2) \times X(4) + 8.610e^{-3} \times X(3) \times X(4) \\
& -0.0857 \times X(1)^2 + 0.023 \times X(2)^2 + 1.364e^{-3} \times X(3)^2 - 7.855e^{-3} \times X(4)^2
\end{aligned}
$$

The parameters bound considered for the development of empirical models are,
2% $\leq$ AC $\geq$ 10%
30% $\leq$ FC $\geq$ 50%
60 °C $\leq$ CT $\geq$ 100 °C.
Bar $\leq$ CP $\geq$ 100 Bar

The main objective of the present investigation is to maximize the TS and FS of the fabricated composite by finding the optimal process parameter settings of each input parameter. Usually, the responses are conflicting with each other. The main aim of the present investigation is to evaluate the optimum parameter settings to obtain maximum TS and FS. Therefore a combined objective function is to be formulated using the weighted sum method. The developed objective function is to maximize both TS and FS is,

$$\text{Maximize(TS + FS)} = \text{w}_1 \times \left(\frac{\text{TS}}{\text{TS}^*}\right) + \text{w}_2 \times \left(\frac{\text{FS}}{\text{FS}^*}\right)$$

TS* and FS* are the maximum tensile strength and flexural strength values obtained from each response by single-objective optimization using RSM-based BBD. Vijayan, Rajmohan [31] formulated a combined objective function using the weighted sum method by assigning equal weight in each factor on the particle swarm optimization (PSO) algorithm. Similarly, in the present investigation, a novel firefly algorithm is applied to find optimal parameter settings of ramie and areca fiber composites.

The Firefly algorithmic parameters considered for the present optimization problems are: no fireflies = 25, Coeffieice of light absorption = 1, the base value of attraction coefficient = 2, mutation coefficient = 0.2, mutation coefficient damping ratio = 0.2, and the maximum number of iterations is 100. Various combinations of these algorithmic factors are used to obtain the best optimal settings of the composite fabrication. The assigned values of mutation coefficient and mutation damping ratio

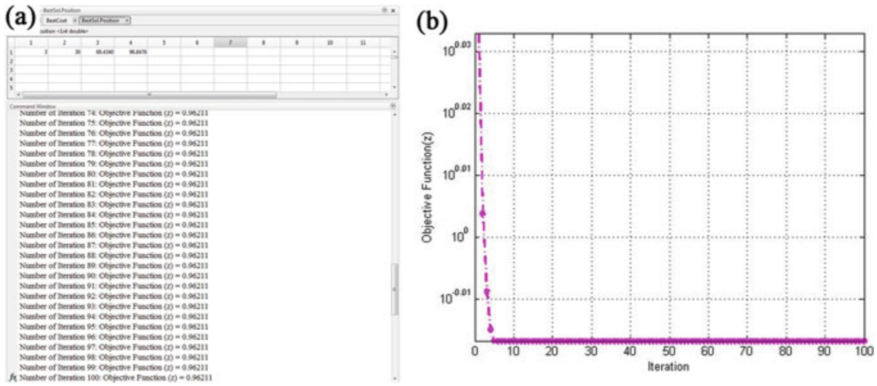


Fig. 9 **a** Convergence plot, **b** Convergence values

Table 3 Predicted optimum fabrication parameters of ramie/areca fiber composite

Alkali concentation (%)	Fiber content (%)	Curing temperature (°C)	Compression pressure (Bar)	Objective function (z)
30	30	100	96.8476	0.96211

allow the firefly algorithm to maintain the 'good optimality' and best' fitness values. Figure 8a, b illustrates the performance of the firefly algorithm across the generations and its corresponding fitness values (Fig. 9).

After the 59th generation, the average fitness values remain the same till the 100th generation. The firefly algorithm randomly makes a population of 100 individuals; it is relatively conceivable to have some individuals much superior to the rest of the population. Between the superior generations progress, the firefly algorithm finds and compares 'best' individual to the optimum of the existing generation and continue to carry forward the better than the existing generation. Table 3 presents the optimum combinations of fabricating parameters predicted by the firefly algorithm.

6 Conclusion

The present investigation proposes a firefly algorithm to investigate the fiber content influence on tensile and flexural strength by varying different fabricating parameters, namely alkali concentration, curing temperature, and compression pressure. The fracture zones of fabricated composite samples are analyzed using SEM images. Based on the mechanical and metallurgical studies performed, the following findings are summarized below,

- The tensile strength increases when increasing alkali concentation from 2 to 6%. However, increasing the alkali concentration beyond 6% decreases the interfacial adhesion between the fiber to the matrix due to excess removal of lignin, hemicellulose, and other natural impurities from the fiber layers decrease the degree of surface roughness on the fiber layers.
- When the composite samples fabricated with 60 °C, especially at a high density of fiber content, produce high tensile strength, it is low when cured with the 80OC to 100 °C. Achieved a maximum tensile strength of 76.25 MPa when the sample cured at 60 °C. Observed many voids and pitted surfaces along the composite surfaces when the composite 'laminated at high temperatures.
- An adequate amount of compression pressure produces a better interfacial bonding on the composite surfaces though the fiber content is low. These findings indicate adequate compression pressure is necessary to fabricate the composite though the fiber content is low or high.
- A good percentage of alkali concentration retains hemicellulose, lignin, and other impurities that increase the composite's flexural strength. The laminated composite achieved the maximum flexural strength of 136.36 MPa.
- Raise of curing temperature from 60 to 80OC increases the flexural strength of the laminated composite. However, excess fiber burnout failed to sustain the same flexural strength on the composite surface.
- The proposed evolutionary algorithm predicted the optimal fabricating parameters and showed its robustness while obtaining a solution based on the desired boundary condition.

References

1. Vijayan D, Thiagarajan R (2020), Influence of Stacking Sequence on Mechanical and Metallurgical Properties of Ramie/areca Laminates Using B4C Nano Filled Epoxy Resin. Journal of Natural Fibers,1–17.
2. Deshmukh PS, Patil PG, Shahare PU, Bhanage GB, Dhekale JS, Dhande KG, Aware VV (2019) Effect of mechanical and chemical treatments of arecanut (areca catechu L.) fruit husk on husk and its fibre. Waste Manage 95:458–465
3. Muneer Ahmed M, Dhakal HN, Zhang ZY, Barouni A, Zahari R (2021), Enhancement of impact toughness and damage behaviour of natural fibre reinforced composites and their hybrids through novel improvement techniques: A critical review, Composite Structures, 259, 113496.
4. Zhao X, Tu W, Chen Q, Wang G (2021), Progressive modeling of transverse thermal conductivity of unidirectional natural fiber composites, International Journal of Thermal Sciences, 162, 106782.
5. Awais H, Nawab Y, Amjad A, Anjang A, Md Akil H, Zainol Abidin MS (2021), Environmental benign natural fibre reinforced thermoplastic composites: A review. Composites Part C: Open Access, 4, 100082.
6. Sumesh KR, Kanthavel K, Kavimani V (2020) Peanut oil cake-derived cellulose fiber: Extraction, application of mechanical and thermal properties in pineapple/flax natural fiber composites. Int J Biol Macromol 150:775–785

7. Singh T, Pattnaik P, Pruncu CI, Tiwari A, Fekete G (2020), Selection of natural fibers based brake friction composites using hybrid ELECTRE-entropy optimization technique. Polymer Testing, 89, 106614.
8. MohanDas CD, Ayyanar A, Susaiyappan S, Kalimuthu R (2017) Analysis of the effects of fabrication parameters on the mechanical properties of Areca fine fiber-reinforced phenol formaldehyde composite using Taguchi technique. Journal of Applied Research and Technology 15(4):365–370
9. Sultana N, Hossain SZ, Alam MS, Hashish M, Islam MJC, Materials B (2020), An experimental investigation and modeling approach of response surface methodology coupled with crow search algorithm for optimizing the properties of jute fiber reinforced concrete, 243, 118216.
10. Hu Z, Vambol O, Sun SJCS (2021), A hybrid multilevel method for simultaneous optimization design of topology and discrete fiber orientation, 266, 113791.
11. Savran M, Aydin L (2021) Chapter Fourteen - Material selection for hybrid natural fiber laminated composites in vibration using a stochastic optimization method. In: Rangappa SM, Siengchin S, Jawaid M, Asiri AM (eds) Khan A. Hybrid Natural Fiber Composites, Woodhead Publishing, pp 281–307
12. Ball AK, Roy SS, Kisku DR, Murmu NC, Coelho LdS (2020), Optimization of drop ejection frequency in EHD inkjet printing system using an improved Firefly Algorithm, Applied Soft Computing, 94, 106438.
13. Xing H-x, Wu H, Chen Y, Wang K (2020), A cooperative interference resource allocation method based on improved firefly algorithm, Defence Technology.
14. Wu J, Wang Y-G, Burrage K, Tian Y-C, Lawson B, Ding Z (2020), An improved firefly algorithm for global continuous optimization problems, Expert Systems with Applications, 149, 113340.
15. Wang Z, Liu D, Jolfaei A (2020) Resource allocation solution for sensor networks using improved chaotic firefly algorithm in IoT environment. Comput Commun 156:91–100
16. Bui D-K, Nguyen T, Chou J-S, Nguyen-Xuan H, Ngo TD (2018) A modified firefly algorithm-artificial neural network expert system for predicting compressive and tensile strength of high-performance concrete. Constr Build Mater 180:320–333
17. Adeyi AJ, Adeyi O, Oke EO, Olalere OA, Oyelami S, Ogunsola ADJAI, Research EP (2021), Effect of varied fiber alkali treatments on the tensile strength of Ampelocissus cavicaulis reinforced polyester composites: Prediction, optimization, uncertainty and sensitivity analysis, 4(1), 29–40.
18. Habibi M, Selmi S, Laperrière L, Mahi H, Kelouwani S (2019) Post-Impact Compression Behavior of Natural Flax Fiber Composites. Journal of Natural Fibers 17(11):1683–1691
19. Jaafar J, Siregar JP, Tezara C, Hamdan MHM, Rihayat T (2019) A review of important considerations in the compression molding process of short natural fiber composites. The International Journal of Advanced Manufacturing Technology 105(7–8):3437–3450
20. Soundhar A, Kandasamy J (2019), Mechanical, Chemical and Morphological Analysis of Crab shell/Sisal Natural Fiber Hybrid Composites, Journal of Natural Fibers, 1–15.
21. Tomo HSS, Ujianto O, Rizal R, Pratama Y (2017), Effects of number of ply, compression temperature, pressure and time on mechanical properties of prepreg kenaf-polypropilene composites, IOP Conference Series: Materials Science and Engineering, 223 (1), 012026.
22. Costa IL, Alves AR (2017) Mulinari DRJPe. Surface treatment of Pinus Elliottii fiber and its application in composite materials for reinforcement of polyurethane 200:341–348
23. Ozerkan NG, Ahsan B, Mansour S, Iyengar SR (2013) Mechanical performance and durability of treated palm fiber reinforced mortars. Int J Sustain Built Environ 2(2):131–142
24. Chowdhury IR, Nash NH, Portela A, O'Dowd NP, Comer AJ (2020), Analysis of failure modes for a non-crimp basalt fiber reinforced epoxy composite under flexural and interlaminar shear loading, Composite Structures, 245,112317.
25. Bharathiraja G, Jayabal S, Kalyana Sundaram S (2017) Gradient-based intuitive search intelligence for the optimization of mechanical behaviors in hybrid bioparticle-impregnated coir-polyester composites. J Vinyl Add Tech 23(4):275–283
26. Banagar AR, Chikkol Venkateshappa S, Shantharam Kamath S, Bennehalli B (2018) Tensile and flexural properties of areca sheath fibers. Materials Today: Proceedings 5(14):28080–28088

27. Bajpai PK, Singh I, Madaan J (2012) Development and characterization of PLA-based green composites. J Thermoplast Compos Mater 27(1):52–81
28. Dhawan V, Debnath K, Singh I, Singh S (2016) Prediction of forces during drilling of composite laminates using artificial neural network. A new approach. FME Transaction 44(1):36–42
29. Singh JIP, Singh S, Dhawan V (2017) Effect of Curing Temperature on Mechanical Properties of Natural Fiber Reinforced Polymer Composites. Journal of Natural Fibers 15(5):687–696
30. Bajpai PK, Singh I, Madaan J (2012) Comparative studies of mechanical and morphological properties of polylactic acid and polypropylene based natural fiber composites. J Reinf Plast Compos 31(24):1712–1724
31. Vijayan D, Rajmohan T (2019) Modeling and evolutionary computation on drilling of carbon fiber-reinforced polymer nanocomposite: an integrated approach using RSM based PSO. J Braz Soc Mech Sci 41(10):1–17

Bio Fibre Composites: Thermal Characterization

Preparation, Mechanical Properties and Thermal Analysis of Basalt Fiber Reinforced with Polypropylene (BFRPP) Composites

S. Vijayabhaskar, T. Rajmohan, Umar Nirmal, and Vemuri Subramanya Somnath Sarma

Abstract Polypropylene considered to be one of the evolving polymers in the locomotive area, besides several investigators primarily concentrating their study on polypropylene composites at present being advantageous in numerous confronting environmental challenges at present situation. The industrial and research applications of composites reinforced with natural fibers have been increased owing to excellent compensations when compared to synthetic fibers. Currently numerous manufacturers in automobile sector concentrate on eco-friendly automobile parts production that can reduce the production cost, besides improved fuel efficiency. The current study is considered based on the fabrication of basalt / polypropylene composite produced through a combined method of hand lay-up techniques. To explore the glass transition temperature (T_g) of the composite thermogravimetric (TGA) analysis was employed. Three-point bending experiment and tensile tests of polypropylene/basalt composites were investigated depending upon the number of basalt fabric layers. The bonding between matrix and basalt fiber at the interface is superior as revealed through SEM and EDX microscopy. The thermal resistance of basalt fibers were optimum at temperature range of 30–900 °C as found through thermogravimetric analysis.

Keywords Scanning Electron Microscopy (SEM) · Polypropylene · Laminated · Thermoplastic · Basalt Fiber

S. Vijayabhaskar (✉) · T. Rajmohan · V. S. Somnath Sarma
Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya, Enathur, Kanchipuram 631561, India

U. Nirmal
Centre of Advanced Mechanical and Green Technology, Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, 75400 Melaka, Malaysia
e-mail: nirmal@mmu.edu.my

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_15

1 Introduction

Polypropylene (PP) has been broadly substituting engineering plastics due to its economic feasibility, weight saving, outstanding mechanical concert, and ease of dispensation and recyclability [1]. Basalt fiber an inorganic, naturally occurring mineral fiber, is majorly utilised as an ecologically friendly, even green reinforcing material used as a matrix in various polymer matrices. Basalt fibre can be incorporated as matching counterpart for glass fiber in numerous applications in various fields of engineering because of their improved characteristic properties [2]. When the basalt fibers are reinforced in a polymer in our study it is polypropylene (PP) matrix, the phrase basalt fiber-reinforced polypropylene (BFRPP) composites are formed. Some of the disadvantages possessed by the BF are on their brittle toughness and stiff nature, i.e. brittle like nature [3]. Konstantinos Karvanis et al. [4] proved that the BFRP composites exhibited very good mechanical strengths due to good interfacial bonding between polymer matrix and the basalt fibers reinforcement. Few researchers have showed in their research that, in contrast to glass fibre reinforced polymer laminates, the presence of basalt layers in the polymer composite increased the mechanical characteristics to the greatest extent in hybrid laminates [5]. Salvatore et al. [6] demonstrated that the BF's offer possible enhancements to have a better flexural modulus and interlaminar properties to hybrid glass/ basalt fiber reinforced polymer composite. The build-up of BFs in epoxy-based carbon fibre reinforced composites boosted the impact characteristics, according to Dorigato and Pegoretti [7].

Basalt Fiber has established growing consideration as an innovative type of reinforcing substance for the development of hybrid composites/laminates [8]. Sarasini et al. [9]. reported that the BF reinforced composite's elastic modulus is strongly influenced by the chemical attraction and arrangement of the individual BF. They proved that the hybrid laminates of carbon and basalt have improved the impact energy with improved resilience near damage compared to laminates made up of individual carbon fibers. Ary Subagia et al. [10] displayed that the flexural strength and tensile were improved by 16%, while arise of 153% and 27% was detected in flexural and tensile modulus using laminates of tourmaline / basalt / epoxy composites. Wang et al. [11] demonstrated that, because of hybridization of the basalt fibre, the composite revealed a trend in increase in the overall modulus, fatigue behaviour and potential strength. BF has exhibited remarkable outstanding impact energy protecting the composite, when the fibers are situated on the first and last layers of the composite or being sandwiched alternatively in the composite [12].

To estimate the thermal stability of composites materials Thermogravimetric analysis (TGA) is frequently utilised. Fiber-reinforced polypropylene (FRPP) composites naturally crumble at range of temperature in between 300–500 °C while releasing toxic volatiles and heat. Landucci et al. [13] showed BF's may possibly be considered as a component used in the creation of innovative thermal shields. Czigany [14] found that apart from its superior mechanical performance, BF has other advantages like as acoustic insulation, good chemical and thermal resistance, and poor water assimilation ability, which makes basalt fiber a good candidate in the field of composite development. Militky et al. [15] proved that fibers exhibited had displayed solid tensile characteristics when the fibers were under temperature influence below 300 °C for a time lower than 60 min. The friction coefficient of the basalt-ceramics hybrid composite increases rapidly as the volume content of BFs increases [16]. The active use of BF composites for the extent of hot gas filtration was demonstrated by Medvedyev and Tsybulya [17]. The authors demonstrated that using BFs into the bag house preparation increases its life duration up to 10 years. Chen et al. [18] established the possibility of in-situ arrangement along with diffusion of functionalized nanotubes in multi-scale epoxy-based laminates reinforced with BFs. Researchers also discovered that by hybridising the surface of BFs with a silane coupling agent, the bonding present in the composite improved, which finally enhanced the physical properties of the composite [19, 20].

Sanga [21] and Plappert [22] compared the physical properties of S-2 glass fibres and E- glass fibres to BFs and concluded that BFs can act as a fire-retardant element due to their high resistance in temperature. Czigány et al. [23] in their research have concluded that the fracture toughness of BF can be increased when reinforced with PP. Balaji et al. [24] have concluded in their literature that, treated basalt fibre with a functional nanomaterial yields a good toughness and stiffness of the composite. Botev et al. [25] in his research showed that the incorporation of BFs in the matrix decreased the strain and stress at yield. They also revealed that there was improper adhesion between the fibers and the matrix which lowered the yield stresses. Addition of untreated short basalt fibres decreases the tensile properties of the sample while adding coupling agent would increase the damping properties of the matrix.

Intense research has been carried out for hybrid polymers so that incorporation of two or more reinforcements would develop the properties of the composite material. Amuthakkannan et al. [26] prepared composites using glass and BFs. They considered various samples of different compositions and tested for mechanical properties. They found out that the flexural modulus and flexural strength with pure stacking of BF was highest among the other samples. When biodegradable polybutylene succinate is reinforced with basalt fibre [27], the impact strength decreased when the fibre loading increased. This was due to fibre pull-out. Deák et al. [28] have proven that silane coupling agents which are generally used as coupling agents for natural fibre reinforced polymers can be used for BFs reinforced composites and they have shown a tremendous increase of impact strength. Živković et al. [29] in his study revealed that water absorbed by the BFs composites is less than the flax fibre reinforcement. Xing, et al. [30] and Kessler et al. [31] concluded that increase in temperature effects the physical properties of the BFRP and decrease the fatigue, tensile strength of the material. Kessler [31] and Moiseevet et al. [32] have less than E-glass fibre reinforced polymers showed more tensile strength than the BFRP composite. At elevated temperatures there is much larger increase in the creep for BRFP [33].

As a result of the above reported research on basalt fibers, BFs can be regarded as eco-friendly, green and non-lethal materials and there is a lot of scope for research and innovation in many economic and engineering fields. This scope is because of their role in improving mechanical, chemical and thermal performances. As a result, the

Table 1 Properties of Basalt Fiber

Density (g/cm^2)	Tensile strength (GPa)	Elastic modulus (GPa)	Elongation (%)	Maximum temperature (°C)
2.62–3.05	3.0–3.5	79.3–93.1	3.2	650

Table 2 Properties of Polypropylene

Density (g/cm^2)	Poisson's ratio	Thermal expansion (μm/m°C)	Thermal conductivity (W/m–k)	Specific heat capacity (J/g-°C)	Heat transfer capacity (J/g-°C)	Friction coefficient
0.9	0.42	100–180	0.15	1.8	24.5	0.1

current study uses a hand lay-up and compression moulding approach to investigate the mechanical performance of locally generated BFs reinforced with PP resin. The strength properties of the basalt fibre reinforced Polypropylene (BFRPP) composite will be investigated through impact, compression, tensile and three-point bending tests subjected to different fibre loading conditions. The glass transition temperature (Tg) of the BFRPP composites will be explored with the help of thermogravimetric analysis (TGA) while the worn surfaces morphology of the tested BFRPP composite will be analysed using SEM imaging to determine failure modes.

2 Materials and Methods

2.1 Material Used

In the current research, polypropylene (PP) in the form of a laminated sheet with 1 mm thickness acquired from Virtue Polymers Hyderabad, Telangana as the matrix material while Basalt fiber in woven mat form (200 gsm) of thickness 0.25 mm was provided by Vaishnavi composites Hyderabad, Telangana. will be utilised as reinforcing elements in PP. The physical and thermal properties of the basalt fibre are mentioned in Table 1 and physical and thermal properties of polypropylene is mentioned in Table 2.

2.2 Preparation of Composites

The laminated composites are fabricated employing hybrid hand layup with compression molding technique which is shown in Fig. 1 . Three sample specimens of size 380 × 170 × 17 mm are processed in conjunction with two different weight proportions

Fig. 1 Compression molding process machine

of basalt fiber and polypropylene. Sample number 1 consists of 60% polypropylene and 40% basalt fiber, i.e. 9 layers of polypropylene and 8 layers of basalt fabric. Second and third samples consists of 70% polypropylene and 30% basalt fiber, i.e. 10 layers of polypropylene and 7 layers of basalt fiber. It is to be noted here that sample 3 differs from the sample 2 in process parameters which were considered during the fabrication of the sample. The prepared samples are shown in Fig. 2. Table 3 represents the process parameters that are employed for this current study

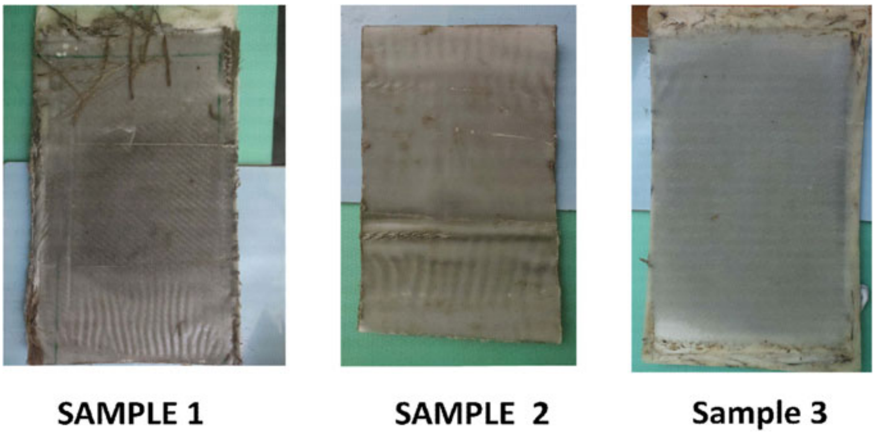


Fig. 2 Fabricated samples

Table 3 Process parameters of compression molding

Specimen	Process Parameters					
	Temperature (°C)	Pressure (bar)	Curing time (min)	Wt % matrix	Wt % reinforcemnet	No of layers
Sample 1	200	100	180	60	40	9P + 8B
Sample 2	220	100	240	70	30	10P + 7B
Sample 2	225	100	300	70	30	10P + 7B

for compression molding process to fabricate the basalt fibre reinforced polypropylene laminated composites. Each sample is placed inside the mold at considered pressure, temperature and the curing time. These parameters are fixed accordingly following application a small amount of releasing agent on both surfaces of the mold. This application of the releasing agent prevents composites from clinging to the mould surface during the curing process.

2.3 Tensile Test

The constructed composite was tensile tested according to the ASTM D638 standard. This tensile test is carried out on a tensile testing machine model: Tinus Olesen UTM where the loading speed was chosen.to be at 5 mm/min. The dimensions of sample that is used for the testing are given in Fig. 3 and these tested sample is shown in Fig. 4. All the three samples were tested to get the average value and their results are tabulated in the Table 4. All of the tests were carried out at a humidity level and room temperature of 80.5% and 28.5 °C respectively.

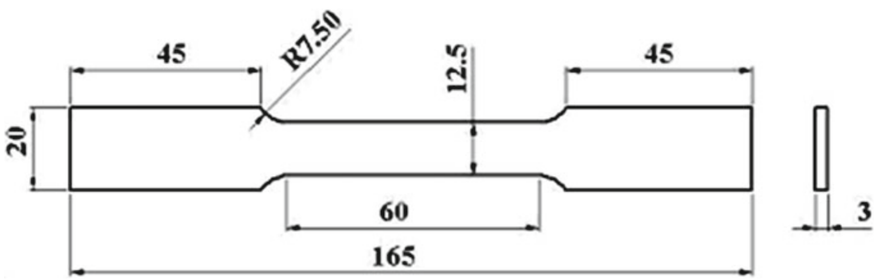


Fig. 3 Specimen Dimensions for tensile test

Fig. 4 Sample being tested in the tensile testing machine

Table 4 Tensile test results of the specimen

S.No	Sample	Sample Composition	Tensile Strength in MPa
1	Sample 1	40% Basalt 60% polypropylene	41.4
2	Sample 2	30% Basalt 70% polypropylene	37.6
3	Sample 3	30% Basalt 70% polypropylene	39.2

2.4 Compressive Test

The ASTM D695 standard was used to create the composite specimens; Fig. 5. The sample is held between the parallel compressive plates, which are parallel to the surface, and then the specimen is squeezed at a constant rate as shown in Fig. 6. Following to this, the maximum compressive load is recorded. Three samples were

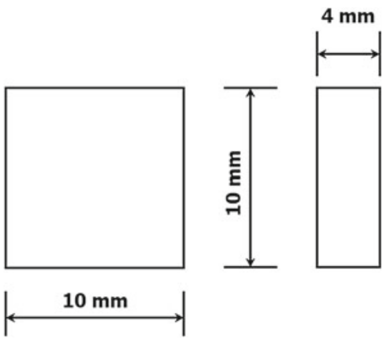


Fig. 5 Specimen dimensions for compressive test

Fig. 6 Sample being tested in compressive testing machine

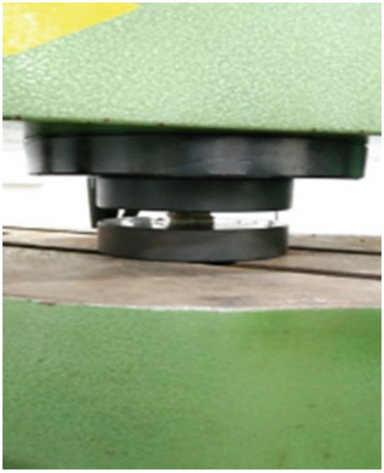


Table 5 Compression Test results of the specimen

S.No	Sample	Sample Composition	Compression Strength in MPa
1	Sample 1	40% Basalt 60% polypropylene	224.6
2	Sample 2	30% Basalt 70% polypropylene	102.1
3	Sample 3	30% Basalt 70% polypropylene	122.2

tested to get the average value. Blocks or cylinders can be used as compressive specimens. For ASTM, the typical block dimensions are 12.7 x 12.7 x 25.4 mm and the cylinders with dimension of 6.35 mm in radius and 25.4 mm long. Speed at which force was applied on the samples was 1.3 mm/min. The compression test values of the samples are presented in Table 5.

2.5 *Flexural Test*

The ASTM D790 standard was followed for the flexural testing of the fabricated composite which was performed using the Tinus Olesen UTM in three-point bending mode. Deflection in the specimen is calculated by the crosshead position. The loading speed was set at 2 mm/min, where the specimen was placed at the designated area while of the machine till the specimen fracture. Figure 7 shows the sample dimensions while the tested samples are shown in Fig. 8 . In all cases, the average is taken, and results are given in the Table 6.

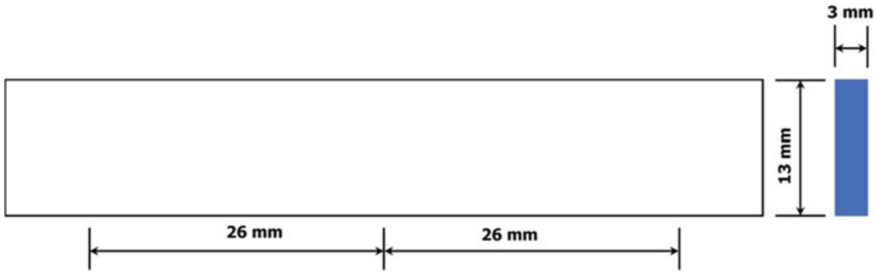


Fig. 7 Sample dimensions for flexural strength

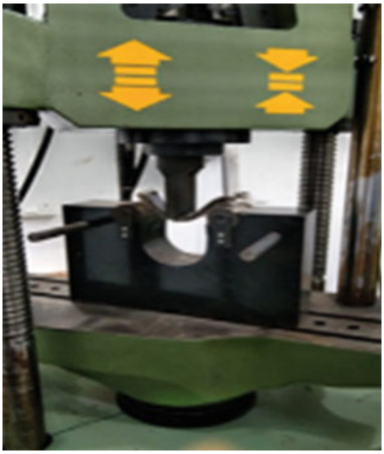


Fig. 8 sample being tested in the flexural testing machine.

Table 6 Flexural Test results of the specimen

S. no	Sample no	Sample Composition	Flexural Strength in MPa
1	Sample 1	40% Basalt 60% polypropylene	78.2
2	Sample 2	30% Basalt 70% polypropylene	68.6
3	Sample 3	30% Basalt 70% polypropylene	108

2.6 Impact Test

The produced composite was subjected to impact testing in Izod mode utilising impact testing equipment in accordance with the ASTM D256 standard. The sample dimensions are shown in Fig. 9. The energy absorbed by the specimen before fracture

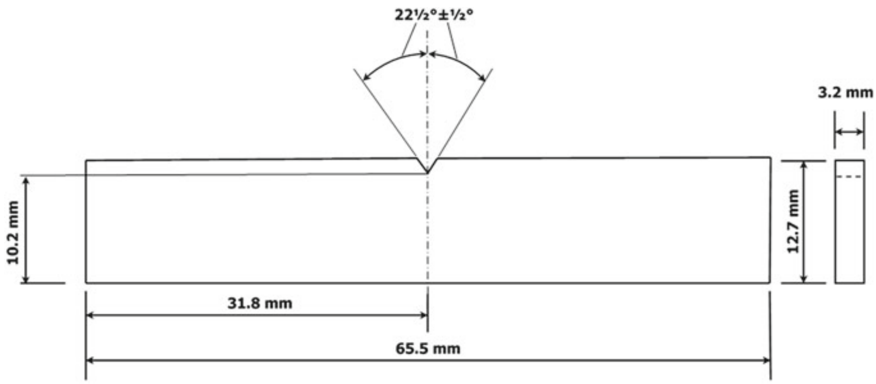


Fig. 9 Sample dimensions for impact strength

Table 7 Impact test results of the specimen

S.No	Sample no	Sample Composition	Impact strength in J
1	Sample 1	40% Basalt 60% polypropylene	14
2	Sample 2	30% Basalt 70% polypropylene	10
3	Sample 3	30% Basalt 70% polypropylene	11

was measured during the test. Three specimens were tested to produce the mean value, which is tabulated in below, Table 7.

2.7 Thermogravimetric Analysis (TGA)

TGA or thermogravimetry (TG) is a procedure where the sample composite small mass is kept under the influence of controlled atmosphere and controlled temperature. Temperature ranges of a typical TGAs is up to 1000 ºC or even more. TGA has been shown to be a method that is relatively dependable, accurate, and quick. [34]. Purge gas which flows through the balance maintains an inert atmosphere like nitrogen, helium or argon. Commercially available thermogravimetric analyser is utilised to thermally decompose samples generally which are present in milligram of weights to determine their thermal stability and weight reduction, researchers used controlled environmental conditions such as controlled heating in the air and in an inert nitrogen atmosphere. [35]. For the current work for TGA, the sample of weight 53.74 mg have been taken and the analysis was conducted using a TGA Q50, TA Instruments; model: NETZSCH STA 449 with a flow and heating rate of 50 mL/min and 10 °C/min throughout a temperature range of 30–550 °C in an oxidising (air) and inert (nitrogen) environment.

TGA is a useful tool intended for determining the thermal stability of materials, particularly polymers. During Thermogravimetry analysis, Volatile and moisture contents of a sample can be calculated by calculating measuring changes in the weight of a specimen with corresponding increase in the temperature when the sample is subjected to the constant heating. There are three different configurations depending on the relative positions of the balance and the furnace. The thermobalance used for our study is bottom loaded thermobalance which uses radiant heating element and a transparent tube to maintain the atmospheric flow. The TGA device's apparatus includes a highly sensitive weight scale calibrator for measuring extremely minute weight changes in the sample and a programmable furnace for controlling and varying the sample's heat. The balance is suspended above the furnace by a hang down wire and is thermally separated from the heat to prevent any loss of heat. The sample pan is hanged at the ending point of the hang-down wire, and its position must be repeatable. To enhance weighing accuracy, sensitivity, and precision, the balance must be insulated from heat effects (e.g., by using a thermostatic chamber). An infrared spectrometer has been added to TGA which enables for the measurement and identification of gases produced by sample's deterioration. The TGA system includes a furnace that helps to quickly cool the sample. The heating element is made of platinum (i.e. withstand temperature up to 1000 °C). An external furnace constructed by an alloy of rhodium and platinum has an ability to extend the temperature range as high as 1500 °C this heating is achieved with the help of heating element. Temperature range for most of the polymers are in between 500–600 °C and constant heating range of 5–20 °C/mm range. All these mass loss processes can be used to determine properties of the polymer such as aging and thermal stability due to the thermo-oxidative processes. These parameters can be utilised to model and to conclude the cure for the sample.

2.8 Differential Scanning Calorimetry (DSC) Analysis

DSC is a most common thermal analysis technique. It analyses a quantitative calorimetric information during a linear temperature ramp, from the sample. DSC is a method of measuring a sample's change in heat flow rate when the temperature changes while the sample is housed in a temperature module. Different qualities such as melting and crystallisation temperatures, heat capacity, and heat of fusion can be measured using DSC in conjunction with discrete thermal parameters of chemical reactions.

In this analysis, the sample is placed on the aluminium pan with a lid on it, that ensures good thermal contact. Weight of the sample is generally around 10 mg, and the weight is measured in an electronic microbalance with an accuracy of 0.1%. Heating, cooling, or isothermal measurements are used on the sample depending on the study's requirements. However, in most cases, DSC is used to evaluate temperatures such as heat of reaction, glass transition temperature crystallisation, and melting point temperature on a polymeric sample. In general, order for DSC experiments is first heating–cooling-second heating. All the results are captured using the supplied software such as the glass transition temperature (T_g), the starting and end temperatures of glass transition temperature T_1 and T_2, the peak melting (T_{mp}), starting temperature and the peak temperature of crystallization (T_{c0}), (T_{cp}), heat of fusion(ΔHf) and heat of reaction(ΔH_{rxn}).

For the current work, DSC experiment was performed using NETZSCH STA 449 where the samples weight was 3.784 mg. The equipment was set with lower temperature 30 °C and maximum temperature of 550 °C, 10 K/min was the heating rate. After that, the sample's thermal characteristics were computed.

3 Results and Discussion

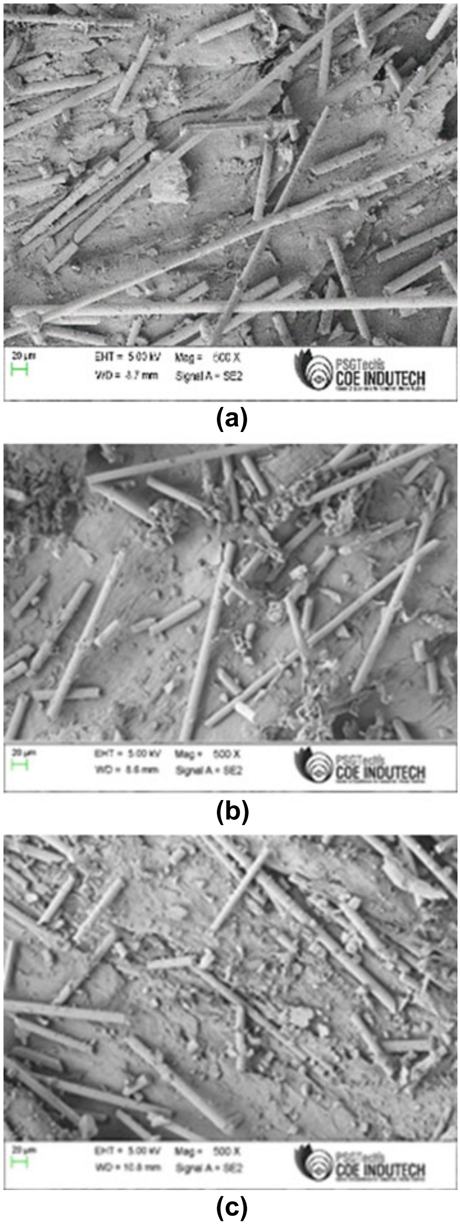
3.1 Microstructure Analysis

Microstructure study was carried out using Scanning Election Microscopy (SEM) and EDX spectroscopy to examine the worn surfaces worn surfaces. The primary worn sample was sliced into 10X10 mm sample dimensions. All the worn surfaces were coated with gold before their SEM images were captured. Figure 10a–c are micrographs of the surface morphology of the BFRPP composite. The roughness of the basalt fibre improves the bonding area between the fibre and the matrix. As a result of the good bonding between the fibre and the matrix, the physical properties of the samples improved [11]. Because tensile stress failure is incomplete and inappropriate, this composite uses multi-layer fabrication, which indicate that multi-layered composites are stronger than mono-layered composites [8]. It is also evident that there exists a good adhesion in between matrix and the reinforcement, which ascertains the increase in sample's physical properties. There are no void spaces observed between the matrix and the reinforcement on all the samples. This verifies good adhesion between the BFs and PP resin.

3.2 Thermogravimetric Analysis

Thermogravimetry analysis (TGA) is a common method for examining the natural fiber's complete thermal steadiness. The thermal dilapidation of natural fiber composites with rise in temperature is examined laterally with arithmetical calculation of quality degradation. Fibre weight drips gradually as the temperature rises, and at glass transition, the fibre's mass drips abruptly for a smaller range before turning to a flat line and finally reactant fatigues. The degradation process in TGA is influenced by the frequency factor, reaction order, and activation energy. Number of factors

Fig. 10 SEM images at 500X of sample 1, sample 2, sample 3 respectively



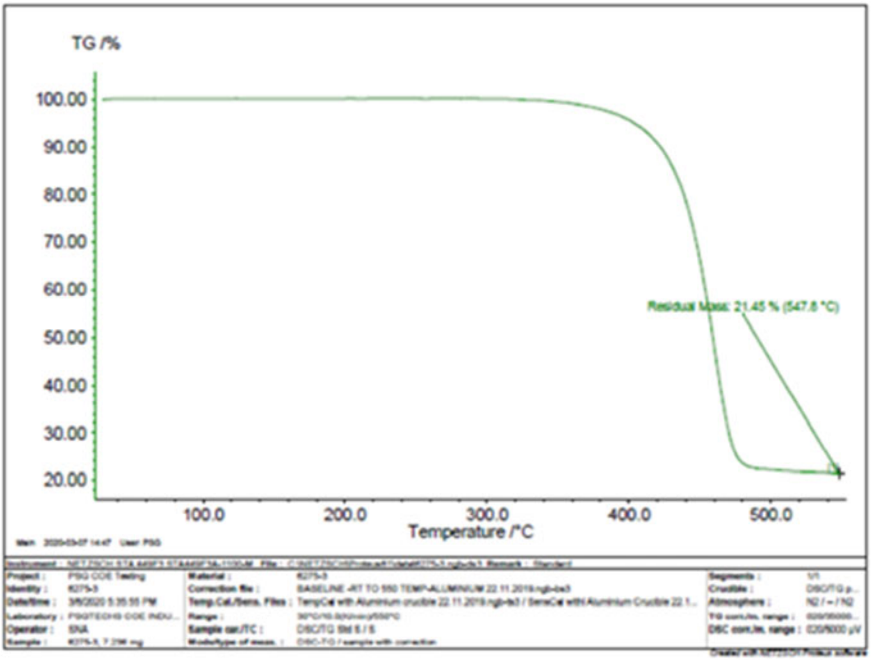


Fig. 11 Thermogravimetry analysis of Sample 1

influence the curve's value, including sample mass, sample shape, atmospheric flow, heating rate, and mathematical treatment.

Figures 11, 12 and 13 represent the weights of the BFRPP composite samples as a function of the temperature, in the range 30–500 °C in air or nitrogen atmosphere. As it can be identified, at the time of decay of the BFRPP composite, at lower temperature, BFs did not decompose in the TG curves, i.e. a sharp decline starts at approximately 400–450 °C, and this specific decline is attributed to the main weight loss of the PP matrix. The BFs were mainly composed of SiO_2 as the main component, Al_2O_3 as the secondary, and other oxide ceramic components, which leads to BFs revealing excellent high temperature resistance performance. Jamshaid et al. [36] showed that basalt fibre reinforced composites underway their thermal decomposition at 363 °C. From Fig. 12, it can be observed that the decomposition of sample 1 with 40% BFs starts to take place from 395 ºC and from Fig. 13 for sample 2, the decomposition starts at a slightly lower temperature of 380 ºC. Figure 14 of sample 3 indicates that the decomposition temperature is around 410 ºC. The final leftover residues of samples 1, 2 and 3 is 36.77%, 34.01% and 21.45% respectively at temperature of 547.8 ºC. The BFRPP composite degraded in two stages namely: the first stage was caused by basalt breakdown at 250 °C, and the second stage was caused by polypropylene decomposition at 320 °C. Hao and Yu [34] revealed in their research that the mass loss in BFs occurs at temperature ranging from 200 to 350 °C. They demonstrated that the presence of many micro-pores in BFs prevent

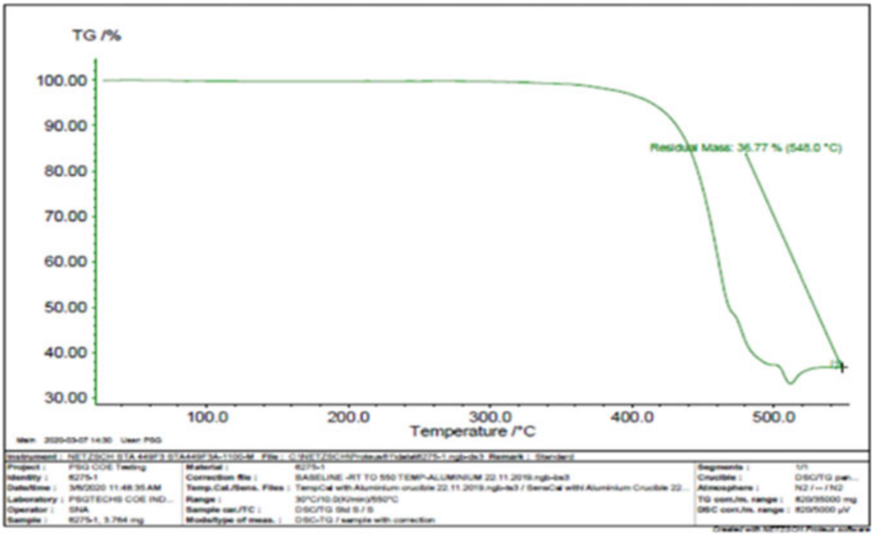


Fig. 12 Thermogravimetry analysis of Sample 2

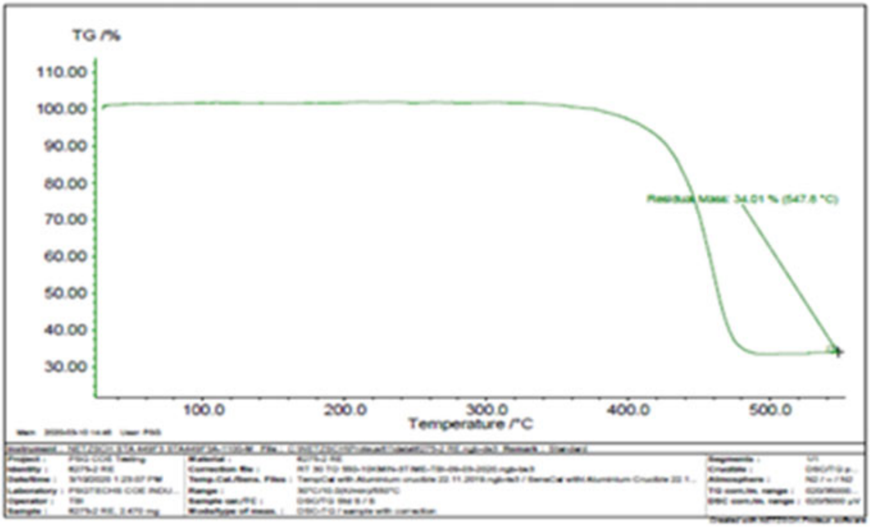


Fig. 13 Thermogravimetry analysis of Sample 3

thermal radiation and convection. The heat deflection temperature (HDT) and Vicat softening temperature (VST) of BF composites were much higher than the ordinary polymeric matrix, according to Zhang et al. [27]. The key influence defining the heat temperature sturdiness of BFs is their ability to crystallise. on the fibre surface. The capacity to crystallise is mostly determined by the chemical composition of the fibre

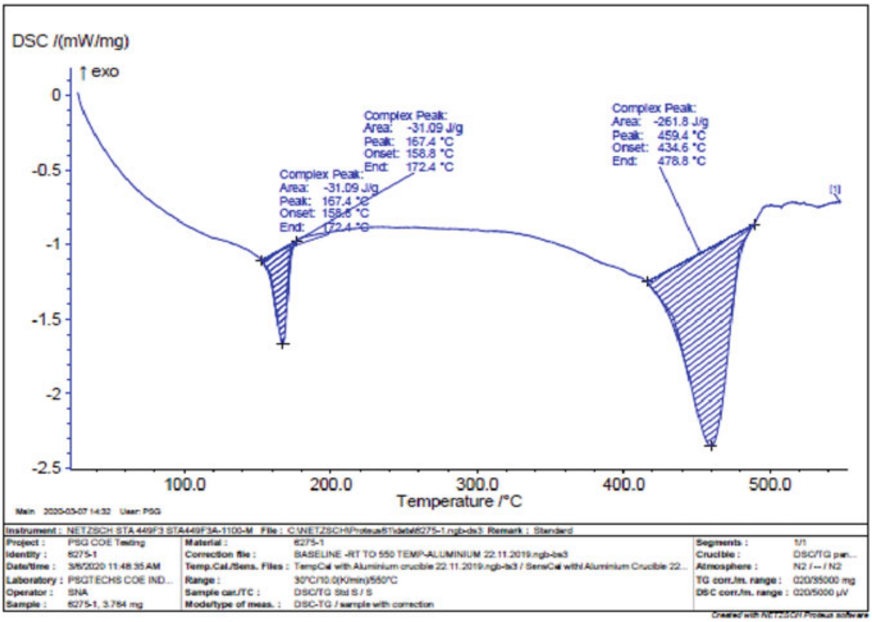


Fig. 14 DSC analysis of Sample 1

as well as the heat treatment parameters. Basalt fibre begins to crystalise as ferrous cations starts oxidation this leads to a formation of spinal structure phase because of the increased oxide content. The mass loss temperature is maximum in the case of basalt fibers and the final temperature of the decomposition is also high for basalt fibers than compared to neat polymer fabricated with other fibers.

3.3 DSC Analysis

DSC is used to determine of the decomposition performance of the BFRPP composites. In DSC analysis, as a function of temperature, the amount of heat required to raise the temperature of a test specimen and reference samples is measured. The samples will be holding same temperature throughout the experiment. Heat flux vs temperature or time is used to plot DSC curves. Samples were evaluated by DSC to bolster the heat transform mechanism in order to better grasp the nature of the thermal behavior of composites. Figures 14, 15 and 16 shows the incline trend of hotness under different temperatures. Heat translation could theoretically explain the interfacial attachment of basalt fibre to PP matrix. The major transform mechanism is composed of two heat travel directions namely exothermic and endothermic. Endothermic peak appeared at temperature in between 160–180 °C; it seems to be

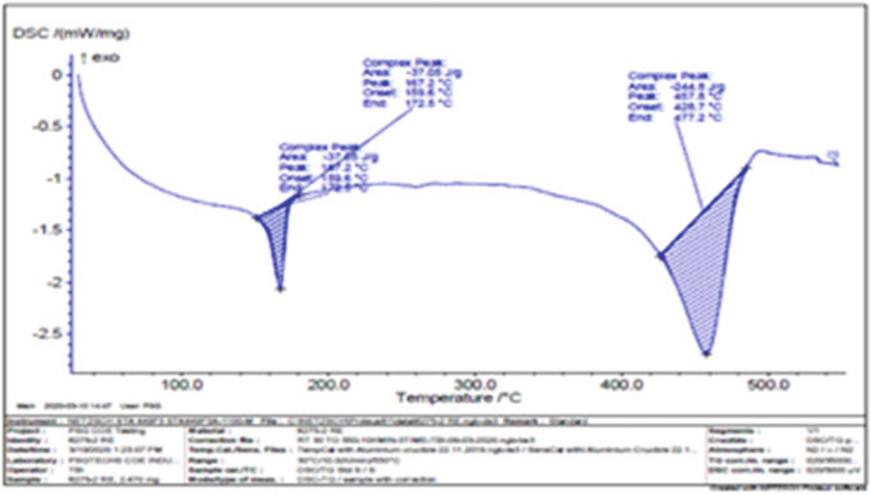


Fig. 15 DSC analysis of Sample 2

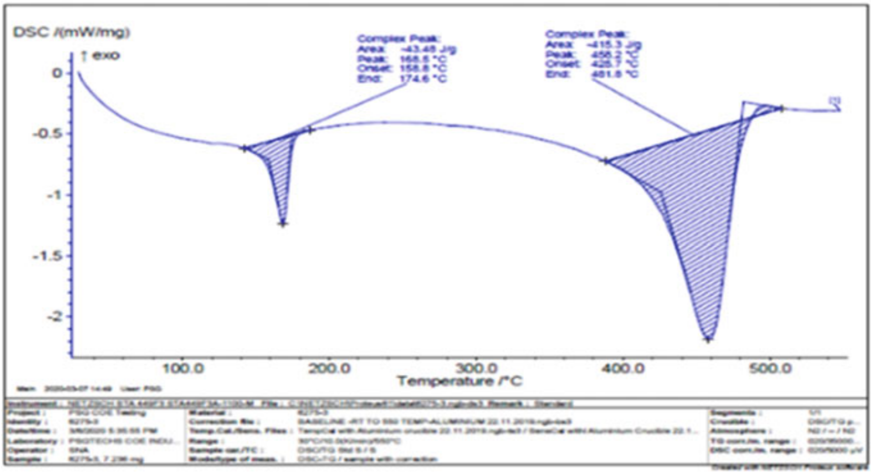


Fig. 16 DSC analysis of Sample 3

occurred by the disappearance of liquid content. At a temperature range of 450–480 °C, the first exothermic peak appeared; this second peak indicates that the chemical reaction is occurring and that heat is being redirected from the primary part to an external part. The endothermic peak reappears when the temperature exceeds 500 °C, owing to the residual degraded polymer mass. The installation of BFs improves the thermal ability of the system. The heat conversion mechanism is strongly linked to the weight loss process of composites; the TG can explain both endothermic and exothermic reactions. The DSC and TG curves are, on the whole, in good agreement with one another.

3.4 Flexural Properties

Flexural property is a property which denotes the flexibility of the material, more the flexibility more brittle will be the material. It is also the ability of the material to resist forces without breakage [38–40]. Flexural properties of specimens are required if the material is used in the structural applications. It can also be used to find the bonding between the reinforcement and the matrix. A 3-point bending test was performed on the sample to ascertain the flexural properties and the results are shown in the below given in Fig. 17. From the graph, it can be inferred that there is highest deformation on the sample 3 and the lowest in sample 2; i.e. flexural modulus decreased from 108 MPa to 78.2 MPa with 10% increase in the BF content. There is about 36.48% decrease in the strength from sample 2 to sample 3 and a decrease of 27.59% from second sample to first sample. Although second and third sample constitute same composition, there is a huge difference in the flexural strengths in the samples. This is because of the better curing time and better bonding between the matrix and the reinforcement. It's also worth noting that sample 1 with more fiber content showed better strength when compared to sample 3. There is a 12.27% increase in the strength with 10% increase in the fiber content.

Figure 18 represents image of the sample 2 after the flexural strength test, there is bend in the sample observed although there is no crack, fiber has expanded and in few areas the bonding between them came off as the sample expanded longitudinally. The failure of the sample is because of the buckling and the improper adhesion between them. From all the observation on flexural properties, increase in reinforcement

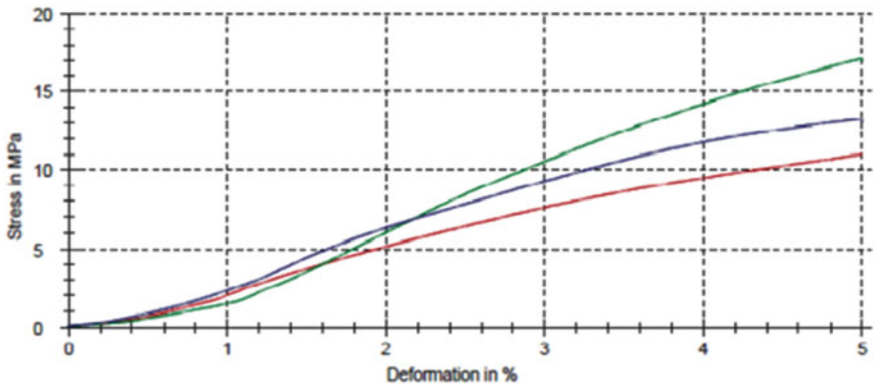


Fig. 17 Flexural strength of the specimen

Fig. 18 Sample 2 after flexural test

weight in the composite increased the flexural strength [41] while, strong bonding in between the reinforcement and the matrix results in higher flexural strength.

3.5 Tensile Properties

Tensile test of the specimen is capacity of the material of structure to withstand the tensile loads that tend to increase size. BFRPP composite showed similar properties as glass fiber reinforced polypropylene [26]. Tensile strength increased with increase in reinforcing content. Following Fig. 19 displays the tensile test results of samples: tensile test of the sample 1 was 41.4 Mpa, for sample 2 and sample 3 the tensile strengths are 37.6 Mpa and 39.2 Mpa. There is an increase of 10% of strength with same percentage increase in the BF content. Though sample 2 and sample 3 consist of same composition, there is a slender increase in the strength for the sample 3. This is because of curing of the sample which is highest among the three samples

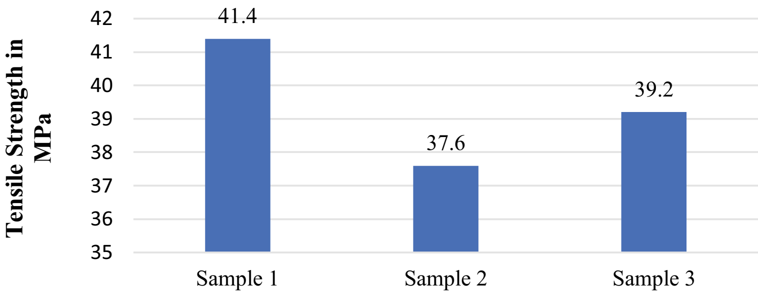
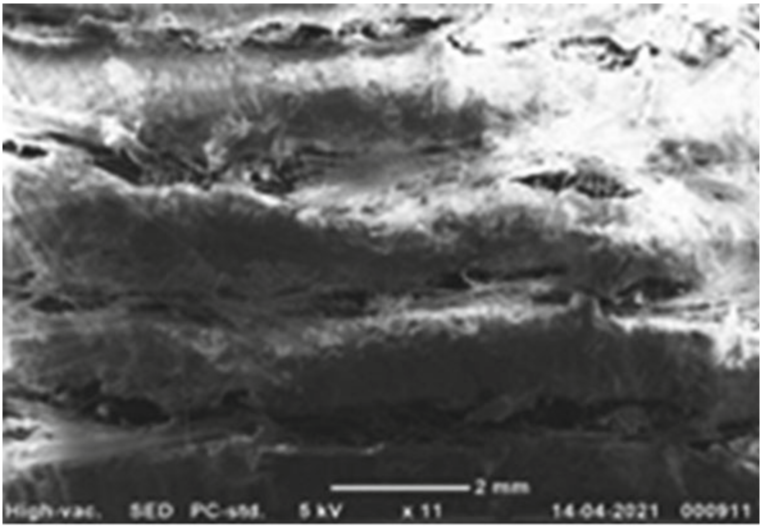
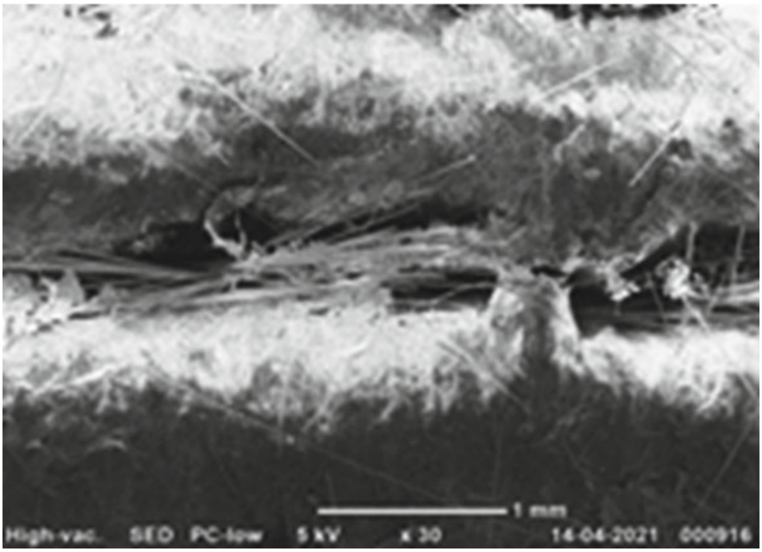


Fig. 19 Tensile strength of samples 1, 2, 3

used in this study. Figure 20a, b illustrates a cut sectional micrographic view of the sample after being tested. The failure of the specimen is because of the breakage of outermost layers of the sample, first and last layers of polypropylene failed initially then the failure passed down to the succeeding layers of the sample. This pattern



(a)



(b)

Fig. 20 Sectional micrograph view after tensile test of failure suggests that there was better bonding in the middle layers than the outer most layers. The breakage occurred on the top region of the sample this also suggests that the bonding between the matrix and reinforcement was not uniform throughout. There is fibre pull-out seen from the reinforcement, this fibre pull-out is also one of the reasons for failure of the specimen.

3.6 Compressive Properties

Compressive strength is the quantity of the element or structure to withstand the compressive loads or the loads which tend to reduce size. Results of the compressive strengths of the three samples are shown in Fig. 21. Sample 1 with more volume percentage of basalt showed a higher compressive strength than the other two samples. An optimal compressive strength of 224.6 MPa is seen in the sample 1, sample 2 showed a compressive strength of 102.1 MPa and the final sample showed a compressive strength of 122.2 MPa. 46% increase in the strength from sample 1 to sample 2 and around 55% increase in the strength from sample 1 to sample 3 is seen. From sample 2 to sample 3, there is a decreasing trend observed in the graph. There is 16% decrease in compressive strength, though both samples constitute similar composition this decline in trend is because of the curing time. Sample 3 had an advantage of better curing time than the sample 2, this advantage is seen clearly in the graph. All the sample are compressed flat, and the fibers tend to expand transversely which showed buckling failure. There were no cracks observed in the matrix. The damage in the samples was due to transverse failure of the sample [42]. Other failure can be seen in the splitting of the fibers and the fibre pull-out.

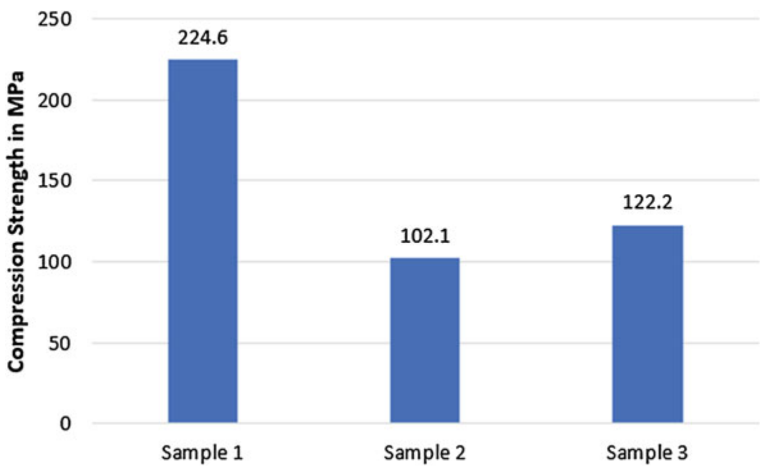


Fig. 21 Compressive strength of samples

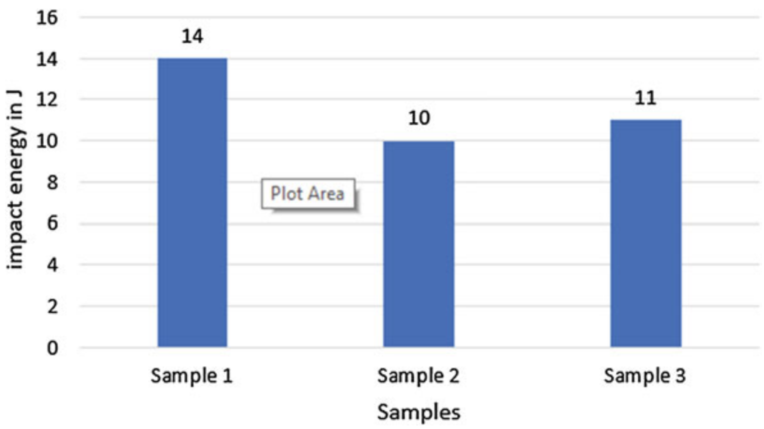


Fig. 22 Impact energy of samples

3.7 *Impact Strength Properties*

The quantity of energy obtained by the sample during fracture is referred to as impact energy. The test results are given in Fig. 22 respectively. For sample 1 with 40% of BF content, the impact strength obtained was 14 J and for sample's 2 and 3 impact strength obtained is 10 J. There is about 28% increase in the impact energy from sample 1 to sample 2 to sample 3. The trend in increase in the impact energy is because of increasing the amount of reinforcement. The increase in reinforcement content also decreased the void spaces between the PP and the basalt fiber. Reinforcement played a crucial role in resisting the crack and absorbing the load which is applied on the matrix. Applied stress is uniformly distributed due to good interfacial bonding strength while the reason for the failure of the sample was fiber pull-out.

4 Conclusions

From the realization of the current work, BFRPP composites of three different samples of different compositions were fabricated using compression molding technique. Three samples of two different compositions: 60% PP—40% BF and 70% PP—30% BF were fabricated. All the three samples were tested with mechanical and thermal tests and from the test results and failure pattern following conclusions are made:

- The optimal tensile strength of 41.4 MPa was seen in sample with 60% PP—40% BF.
- The maximum compression strength of 224.6 MPa was observed in the sample with 60% PP—40% BF which was around 55% more than the compression strength of the sample with 70% PP—30% BF.
- Flexural strength was maximum (i.e. 108 MPa) for sample: 70% PP—30% BF. This significant increase was because of better curing time and the presence of good bonding between matrix and reinforcement.
- Impact strength was seen highest in sample with 60% PP—40% BF (14 J) while sample with 70% PP—30% BF showed impact energy of 10 J—11 J respectively. Impact energy increased when the amount of BFs used in the resin matrix increased.
- SEM micrographs showed good interfacial bonding between the matrix and the reinforcement.
- Main reasons of failure in the samples were fiber pull-out and specimen buckling.
- DSC report showed that the addition BF improved the thermal resistance of the composite.
- TGA analysis showed the final temperature of decomposition was 547.8 °C with around 30% of residual mass.

References

1. Miller L, Soulliere K, Sawyer-Beaulieu S, Tseng S, Tam E (2014) Challenges and alternatives to plastics recycling in the automotive sector. Materials (Basel) 7(8):5883–5902
2. Živković I, Fragassa C, Pavlović A, Brugo T (2017) Influence of moisture absorption on the impact properties of flax, basalt and hybrid flax/BF reinforced green composites. Compos B Eng 111:148–164
3. Fiorea V, Scalicia T, Di Bellab G, Valenzaa A (2015) A review on basalt fibre and its composites. Compos B Eng 74:74–94
4. Konstantinos Karvanis, Sona Rusnáková, OndrejKrejcí, Milan Žaludek, Preparation, Thermal Analysis, and Mechanical Properties of Basalt Fiber/Epoxy Composites, Polymers, 12, 1785
5. Fiore V, Di Bella G, Valenza A (2011) Glass–basalt/epoxy hybrid composites for marine applications. Mater Des 32(4):2091–2099
6. Carmisciano S, Rosa IMD, Sarasini F, Tamburrano A, Valente M (2011) Basalt woven fiber reinforced vinylester composites: Flexural and electrical properties. Mater Des 32:337–342
7. Dorigato A, Pegoretti A (2014) Flexural and impact behaviour of carbon/basalt fibers hybrid laminates. J Compos Mater 48(9):1121–1130
8. Liu Q, Shaw MT, Parnas RS, McDonnell A-M (2016) Investigation of basalt fiber composite mechanical properties for applications in transportation. Polym Compos 27(1):41–48
9. Sarasini F, Tirillò J, Ferrante L, Valente M, Valente T, Lampani L, Gaudenzi P, Cioffi S, Iannace S, Sorrentino L (2014) Drop-weight impact behaviour of woven hybrid basalt–carbon/epoxy composites. Compos B Eng 59:204–220
10. Ary Subagia IDG, Tijing LD, Kim Y, Kim CS, Vista IV FP, Shon HK (2014) Mechanical performance of multiscale basalt fiber–epoxy laminates containing tourmaline micro/nano particles. Compos B Eng 58:611–617
11. Wang X, Wu, Zhishen, Wu, Gang, Zhu H, Zen F (2013) Enhancement of basalt FRP by hybridization for long-span cable-stayed bridge. Compos B Eng 44(1):184–192

12. Ricciardi MR, Papa I, Coppola G, Lopresto V, Sansone L, Antonucci V (2021) Effect of Plasma Treatment on the Impact Behavior of Epoxy/Basalt Fiber-Reinforced Composites: A Preliminary Study. Polymers 13(8):1293
13. Landucci G, Rossi F, Nicolella C, Zanelli S (2009) Design and testing of innovative materials for passive fire protection. Fire Saf J 44(8):1103–1109
14. Czigány T (2006) Special manufacturing and characteristics of basalt fiber reinforced hybrid polypropylene composites: mechanical properties and acoustic emission study. Compos Sci Technol 66:3210–3220
15. Jiří Militký, Vladimír Kovačič, Jitka Rubnerová, (2002) Influence of thermal treatment on tensile failure of basalt fibers. Eng Fract Mech 69(9):1025–1033
16. Öztürk B, Arslan F, Öztürk S (2007) Hot wear properties of ceramic and basalt fiber reinforced hybrid friction materials. Tribol Int 40:37–48
17. Medvedyev O, Tsybulya Y (2005) Basalt use in hot gas filtration. Filtr Sep 42(1):34–37
18. Chen W, Shen H, Auad ML, Huang C, Nutt S (2009) Basalt fibre–epoxy laminates with functionalized multi-walled carbon nanotubes. Compos A Appl Sci Manuf 40:1082–1089
19. Kim MT, Rhee KY (2011) Flexural behaviour of carbon nanotube-modified epoxy/basalt composites. Carbon Letters 12(3):177–179
20. Kim MT, Rhee KY, Kim HJ, Jung DH (2012) Effect of moisture absorption on the flexural properties of basalt/CNT/epoxy composites. Carbon Letters 13(3):187–189
21. Singha K (2012) A short review on basalt fiber, International Journal of Textile. Science 1(4):19–28
22. Plappert D, Ganzenmüller GC, May M, Beisel S (2020) Mechanical Properties of a Unidirectional Basalt-Fiber/Epoxy Composite. Journal of Composites Science 4(3):101. https://doi.org/10.3390/jcs4030101
23. Czigány T, Vad J, Pölöskei K (2015) Basalt fiber as a reinforcement of polymer composites. Periodica Polytechnica Mechanical Engineering 49(1):3–14
24. Balaji K. V, Kamyar Shirvanimoghaddam, Guru Sankar Rajan, Amanda V.Ellis, Minoo Naebe (2020), Surface treatment of Basalt fiber for use in automotive composites, Materials Today Chemistry, 17, 100334.
25. Botev M, Betchev H, Bikiaris D, Panayiotou C (1999) Mechanical properties and viscoelastic behavior of basalt fiber-reinforced polypropylene. J, Applied Polymer Science 74(3):523–531
26. Amuthakkannan P, Manikandan V, Uthayakumar M (2014) Mechanical Properties of Basalt and Glass Fiber Reinforced Polymer Hybrid Composites. J Adv Microsc Res 9(1):44–49
27. Zhang Y, Yu, Chunxiao, Chu PK, Lv F, Zhang C, Ji J, Zhang R, Wang H (2012) Mechanical and thermal properties of basalt fiber reinforced poly (butylene succinate) composites. Mater Chem Phys 133:845–849
28. Deák T, Czigány T, Tamás P (2010) Enhancement of interfacial properties of basalt fiber reinforced nylon 6 matrix composites with silane coupling agents. Express Polym Lett 4:590–598
29. Živković I, Fragassa C, Pavlović A, Brugo T (2016) Influence of moisture absorption on the impact properties of flax, basalt and hybrid flax/basalt fiber reinforced green composites. Compos B Eng 111:148–164
30. Zhao X, Wang X, Wu, Zhishen, Keller T, Vassilopoulos AP (2019) Temperature effect on fatigue behavior of basalt fiber-reinforced polymer composites. Polym Compos 40(6):2273–2283
31. Kessler E, Gadow R, Straub J (2016) Basalt, glass and carbon fibers and their fiber reinforced polymer composites under thermal and mechanical load. AIMS Materials Science 3(4):1561–1576
32. Moiseev EA, Gutnikov SI, Malakho AP, Lazoryak BI (2008) Effect of iron oxides on the fabrication and properties of continuous glass fibers. Inorg Mater 44:1026–1030
33. Lu, Zhongyu, Xian G, Rashid K (2017) Creep Behavior of Resin Matrix and Basalt Fiber Reinforced Polymer (BFRP) Plate at Elevated Temperatures. Journal of Composite Science 1(1):3. https://doi.org/10.3390/jcs1010003
34. Hao LC, Yu WD (2010) Evaluation of thermal protective performance of basalt fiber nonwoven fabrics. J Therm Anal Calorim 100:551–555

35. Kim S-S, Ly HV, Kim J, Choi JH, Woo HC (2013) Thermogravimetric characteristics and pyrolysis kinetics of Alga *Sagarssum* sp. biomass. Biores Technol 139:242–248
36. Jamshaid H, Mishra R, Militky J, Pechociakova M, Noman MT (2016) Mechanical, thermal and interfacial properties of green composites from basalt and hybrid woven fabrics. Fibers and Polymers 17:1675–1686
37. Chunhong Tang, FengXiang Xu, Guangyao Li (2019), Combustion Performance and Thermal Stability of Basalt Fiber-Reinforced Polypropylene Composites. Polymers (Basel),11(11), 1826
38. El-Shekeil YA, Sapuan SM, Abdan K, Zainudin ES (2012) Influence of fiber content on the mechanical and thermal properties of Kenaf fiber reinforced thermoplastic polyurethane composites. Mater Des 40:299–303
39. Mohan K, Rajmohan T (2017) Fabrication and Characterization of MWCNT Filled Hybrid Natural Fiber Composites. Journal of Natural Fibers 14(6):864–874
40. John K, Venkata Naidu S (2004) Sisal Fiber/Glass Fiber Hybrid Composites: The Impact and Compressive Properties. J Reinf Plast Compos 23(12):1253–1258
41. Bernasconi A, Davoli P, Basile A, Filippi A (2007) Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6. Int J Fatigue 29(2):199–208
42. Bandaru AK, Patel S, Sachan Y, Suhail Ahmad R, Alagirusamy NB (2016) Mechanical behavior of Kevlar/basalt reinforced polypropylene composites. Compos A Appl Sci Manuf 90:642–652

Thermal Characterisation of Bio Fibre Composites

Mariana D. Banea, Jorge S. S. Neto, and Henrique F. M. Queiroz

Abstract The bio fibre composites thermal stability is an essential factor to consider, as the processing temperature plays a critical role in the manufacturing process of composites. At higher temperatures, the natural fibre components (i.e., cellulose, hemicellulose, and lignin), start to degrade and their properties change. Different methods are used in the literature to determine the thermal properties of bio fibre composite materials as well as to help to understand and determine their suitability for a particular application. The thermal stability of composites is investigated using TGA, DSC and DMA. The most frequent thermal properties evaluated by these methods are the weight loss percentage, the degradation temperature, T_g and viscoelastic properties. This chapter presents the main techniques used for thermal analysis of bio fibre composites. The main factors that affect the thermal properties of bio fibre composite materials (fibre and matrix type, the presence of additive fillers, fibre content, and fibre orientation, the chemical treatment of the fibres, manufacture process, and type of loading) are briefly discussed.

Keywords Natural fibre reinforced composite material · Thermal analysis · Thermogravimetric analysis (TGA) · Differential scanning calorimetry (DSC) · Differential Mechanical Thermal Analysis (DMA)

1 Introduction

Composites are increasingly being used in various industries, particularly in aerospace industries [1]. Nowadays, the industry is seeking new desirable characteristics of composite materials, eco-friendliness and low cost. Consequently, there has been significant interest in research and innovation in bio fibre composites, owing to

M. D. Banea (✉)
Department of Mechanical Engineering, Federal Center for Technological Education of Rio de Janeiro (CEFET/RJ), Av. Maracanã, Rio de Janeiro 229, 20271-110, Brazil

J. S. S. Neto · H. F. M. Queiroz
Federal Center for Technological Education of Rio de Janeiro (CEFET/RJ), Av. Maracanã, Rio de Janeiro 229, 20271-110, Brazil

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_16

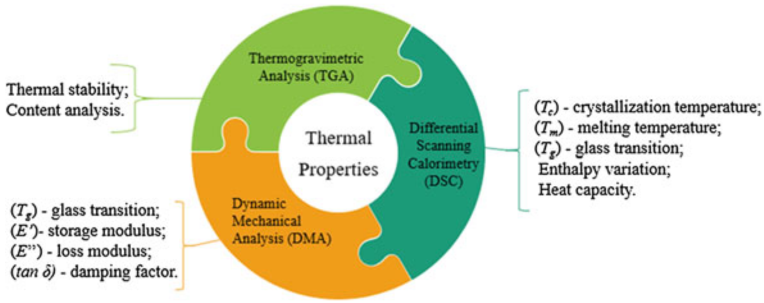


Fig. 1 The main methods for determining the thermal characteristics of composites are depicted in this diagram

the advantages of these materials compared to their synthetic fibre counterparts (i.e., lower environmental impact and low cost), supporting their potential across a wide choice of applications in several industrial sectors [2–7].

The methods used in the literature for thermal analysis of bio fibre composites are as follows: TGA, DSC, DMA. Figure 1 summarises the main methods used in the literature to determine the thermal properties of bio fibre composite materials.

Different methods are used to determine the thermal properties of bio fibre composites and also helps to understand and determine the suitability of bio fiber composites for a particular application. This chapter presents an overview of the main techniques used for the thermal analysis of bio fibre thermoset composites. The main factors that affect the thermal properties of bio fibre composite materials (fibre and matrix type, fibre content and arrangements, the treatment of the bio fibres) are briefly discussed.

2 Thermogravimetric Analysis (TGA)

TGA analysis measures the weighted temperature sample in specific controlled atmosphere (e.g. nitrogen, helium, air, or other gases) [8, 9]. Different temperatures and measurement times are applied in accordance with the matrix type of the bio fibre composite sample [10]. The TGA analysis's thermal data depends on several parameters, sample mass, sample form, atmosphere, flow rate, heating rate, and the treatment applied [10].

The thermal behaviour of biocomposites depends on the composite's principal constituents (bio fibres and matrix type). In general, the derivative thermogravimetric test (DTG) curve of bio fibres shows the elimination of water and the thermal decomposition of cellulose components of the fibres. The DTG curve and peaks in each degradation range indicate fibre constituents. For instance, the lignocellulose [11–15].

Several authors used thermogravimetric analysis to determine the thermal properties of bio fibre composites [16–23]. For example, Arulmuruganet al. [23], studied the effect of barium sulfate (BaSO4) on the thermal properties of an aloe vera/flax hybrid composite. The fibres were subjected to chemical pretreatment (sodium hydroxide and potassium permanganate) with 10% and 5% for one h, respectively. Then they were treated with sodium laurel sulphate with 2% for 30 min. The configurations studied were: 4 layers of aloe verafibre (HNRP1), four layers of flax fibre (HNRP2), two layers of flax fibre + 2 layers of aloe verafibre (HNRP3), four layers of aloe verafibre + 5% of BaSO4 (HNRP4), four layers of flax fibre + 5% of BaSO4 (HNRP5), two layers of flax fibre + 2 layers of aloe verafibre + 5% of BaSO4 (HNRP6). The authors report that the increase in BaSO4 in pure and hybrid composite increased the thermal resistance of HNRP. Moreover, the maximum peak for the treated composites shows an increment with the addition of BaSO4 in its structure.

Hidalgo–Salazar et al. [24], studied the thermal properties of Fique fibre reinforced bio composites. The bio fibre composite were manufactured with two types of resin: Linear Low-Density Polyethylene (LLDP) and Epoxy resin (EP). The fabrication method used was thermo compression and resin film infusion processes. Figure 1 shows TG (Fig. 1a) and DTG (Fig. 1b) curves of the Fique fibre, which reveal that degradation occurred at 296 °C, whereas decomposition of the neat EP begins at 96 °C. As a result, the EP/Fique samples decomposed after the neat resin in both degradation phases. This has previously been observed in the literature for EP/Phormium Tenax leaf fibre composites and was explained due to an improved fibre/matrix interface [25]. After final degradation, the residual char for epoxy resin was 6.1 per cent and 11.1 per cent for epoxy-Fique bio fibre composite. According to the authors, the Fique fibre insertion on the epoxy resin increased the residual char of the composite.

Figure 2 shows TG and DTG curves of LLDPE and LLDPE/Fique bio-composites, whereas Fig. 3 shows thermal curves for EP and EP/Fique bio-composites, respectively. For the neat LLDPE sample, a single step degradation was observed with T_o (onset) at 439 ºC and T_{max} and 478 ºC, correspondingly (see Fig. 2a). The char residue

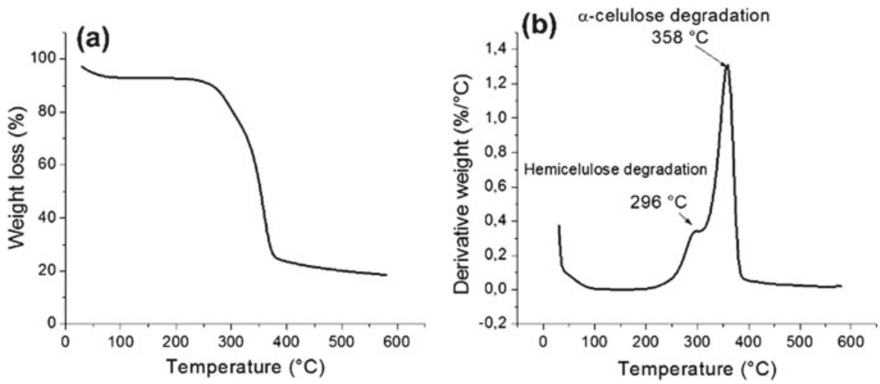


Fig. 2 **a** TG and **b** DTG curves of Fique fibres at heating rates of 10 °C/min. Reproduced with permission from [24]

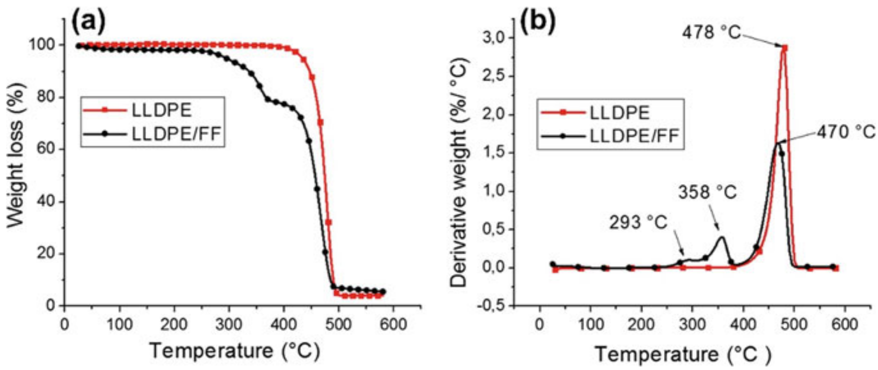


Fig. 3 **a** TG curve of neat Linear Low-Density Polyethylene (LLDPE) and **b** DTG curve of Linear Low-Density Polyethylene nonwoven Fique Fibre biocomposite (LLDPE/FF). Reproduced with permission from [24]

at the end of degradation was 4.1%. For the PE/Fique case, a two-step degradation process was observed. The authors state that the first degradation step is linked to the fibre constituent degradation (T_0 at 266 °C), presenting a mass loss of 21%. A slight decrease in the polymeric matrix's thermal stability was detected, connected to fibre breakdown 170 °C thermos-compression. Due to the addition of Fique fibre, the residual weight increased to 5.6 per cent. From Fig. 2b it can be seen that the DTG curve presented two T_{max} peaks at 293 °C and 358 °C, which can be linked to hemicellulose and α-cellulose degradation. The second degradation step is related to LLDPE matrix decomposition. The process starts at 437 °C and presents a T_{max} of 470 °C. On the other hand, a two-stage weight loss process was reported composites, indicating a similar thermal degradation behaviour (see Fig. 3). In addition, the disintegration of the significant polymeric chain is demonstrated in the second degrading step (250 °C–500 °C). For EP and EP-Fique, the observed T_o were 344 °C and 352 °C, respectively, while T_{max} was 365 °C and 373 °C.

Chin et al. [16] investigated bamboo fibre reinforced composites' mechanical and thermal characteristics in three types of thermoset matrices (epoxy, polyester, and vinyl ester). The fibres underwent two types of treatment: chemical (10% de NaOHbest case) and physical (milling method). The authors analyzed the following volumetric variations: 0%, 10%, 20%, 30% and 40%, whereas the manufacturing method used in the study was hand-lay-up. TGA was used to measure the effect of treatment of the decomposition of bamboo fibres as a function of the type of resins. Figure 4a shows an example of TGA curves of untreated and treated bamboo fibres with different chemical concentrations and times. It was found that the best case was 10% NaOH because of the hydrophilic reduction of the fibre when compared to the untreated fibre.

Furthermore, the concentration of chemical treatment eliminates several constituents, such as hemicellulose. Figure 5b–d shows the degradation of bamboo fibre as a function of temperature for three types of resin.

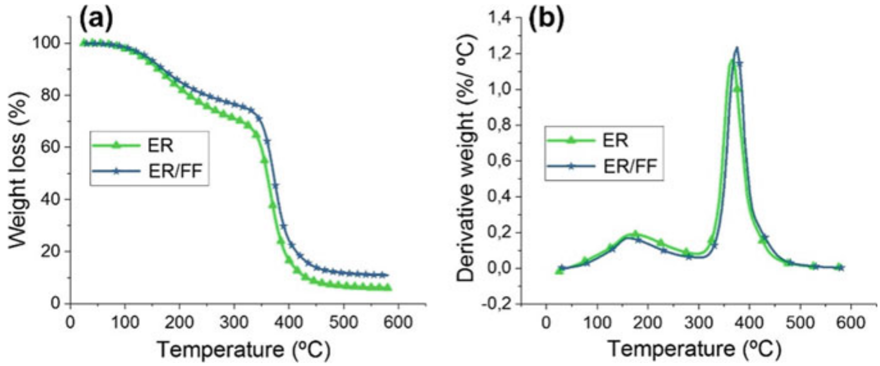


Fig. 4 **a** TG and **b** DTG curves of neat Epoxy resin (EP) and Fique biocomposite based Epoxy (EP/FF). Reproduced with permission from [24]

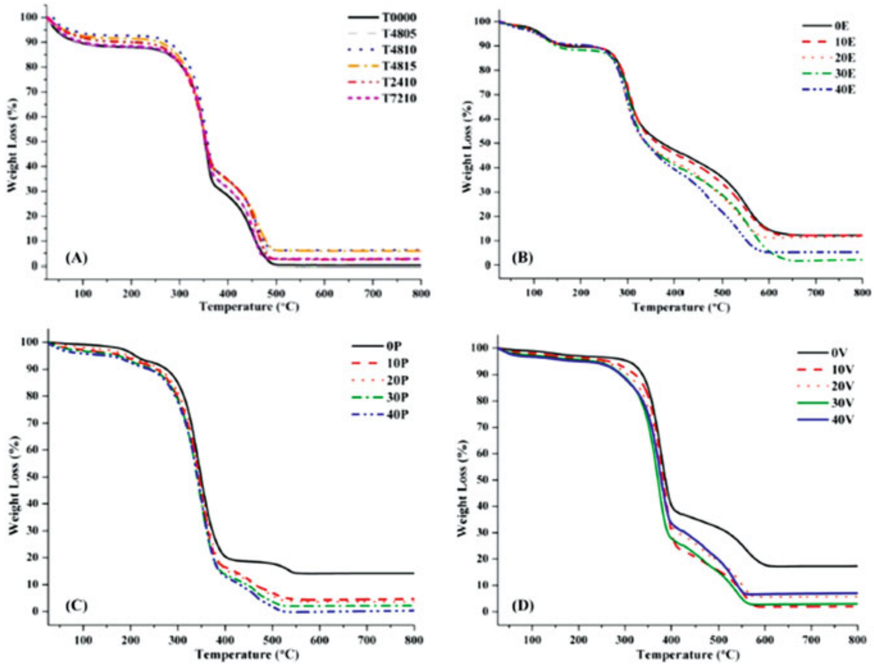


Fig. 5 TGA curves of bamboo fibre and its composites: and different types of resins: **a** bamboo fibre treated at different NaOH concentrations and soaking time **b** bamboo fibre reinforced epoxy composites, **c** bamboo fibre reinforced polyester and **d** bamboo fibre reinforced vinyl ester composites. Reproduced with permission from [16]

Rashid et al. [19], studied the effect of treatments on the mechanical and thermal properties of the sugar reinforced composite based on phenolic resin. The natural fibres underwent two types of treatment: the first was alkalization (0.5% of NaOH) for four h, the second was the washing of the fibres with distilled water. The manufacturing method used was compression moulding using a hot press. The results obtained showed that the first peak was lower for the case treated by mercerization when compared to the other cases: washed and untreated. The authors report that the chemical treatment applied reduced the hydrophilicity of natural fibre in composites. The best case was found for the untreated composite with a value of 430.97 °C, while for the treated and washed case, the maximum peak was 426.99 °C and 423.61 °C, respectively.

Lavoratti et al. [18] analyzed the thermal characteristics of composites reinforced with buriti and ramie fibre. The natural fibres were washed in distilled water and treated with NaOH (2.5 and 10%). The composites were produced by resin transfer moulding (RTM). The authors report that the buriti fibre starts to degrade at 217 °C, while for the ramie fibre, the degradation starts at 247 °C. The maximum degradation temperature obtained after washing with distilled water showed an enhancement in the thermal stability of the biocomposites. However, the alkalization treatment of these fibres negatively affected their thermal properties compared to natural and washed cases.

Nimanpure et al. [22], investigated the effect of hybridization between sisal (S) and kenaf (K) bio-fibre in polyester (P) based composites. The mechanical, electrical, and thermal properties were analyzed. The natural fibres were treated by alkalization with 5% NaOH for 48 h at room temperature. The configurations studied were: SK10P90 (Sisal-5% + Kenaf-5%), SK20P80 (Sisal-10% + Kenaf-10%), SK30P70 (Sisal-15% + Kenaf-15%), SK40P60 (Sisal-20% + Kenaf- 20%), S40P60 (Sisal-40%) and K40P60 (Kenaf- 40 compared to the composite samples reinforced by pure fibres (K40P60 and S40P60).

Cavalcanti et al. [21] used the TGA analysis to study the thermal proeprties of bio fibre composite based on polyester and epoxy resins. The jute + curauá and pure jute fibre composites did not undergo any chemical treatment, whereas the jute + sisal fibre composite was submitted to chemical alkalization treatment. They found that the thermal stability of epoxy-based composites was greater compared to the polyester-based composites. The epoxy-based composite presented a degradation onset temperatures of 318 °C and 317 °C for the jute and jute + curauá cases, while the polyester-based jute and jute + curauá cas-es presented onset temperatures of 310 °C and 312 °C, respectively.

Asim et al. [20], used TGA to analyse the effect of silane treatment on the thermal properties of pineapple (PALF) and Kenaf (K) fibre composites based on phenolic resin. The natural fibre were treated in distilled water with silane (2% for 3 h). The studied cases were 70(PALF):30(Kenaf) – (7P3K), 50P:50 K (1P1K), 30P:70 K(3P:7 K), treated (T-7P3K), (T-1P1K) and (T-3P7K). They found that the T-3P7K and T-7P3K composites were the cases with the highest thermal stability. Moreover, the treated composite presented a higher onset temperature than the untreated composites. Table 1 summarizes the thermal properties of bio fibre composites.

Table 1 TGA research revealed the thermal characteristics of bio fibre composites

Fibre	Matrix	Thermal Properties	References
Bamboo	Epoxy, Polyester and Vinyl ester	The inclusion of bamboo fibre to the composites did not result in a substantial reduction in the composites' initial onset degradation temperature (T_{onset}) of the composites	[16]
Buriti and ramie	Polyester	The maximum peak of degradation temperature (T_d) for the ramie fibre reinforced composite was 372 °C while for the buriti compositea value of 346 °C was reported	[18]
Sisal, sisal + curauá and sisal + ramie	Epoxy	The hybridization increased the thermal stability of the composites when compared to the pure sisal composites	[17]
Sugar Palm	Phenolic	The chemical treatment negatively affected the thermal stability of the composite	[19]
Sisal fibril + kenaf	Polyester	The thermal stability of hybrid composites was superior to pure fibres	[22]
Jute, jute + sisal and jute + curauá	Epoxy and Polyester	The onset temperature (T_{onset}) was higher for the jute, jute + curauá based on epoxy composite compared to polyester composites. For jute + sisal there was no significant change in$T_{onset}$for both matrices	[21]
Kenaf + pineapple	Phenolic	The treated hybrid composites decreased the amount of water and increased the maximum degradation temperature (T_d) when compared to the untreated cases	[20]
Flax + aloevera	Epoxy	The chemical treatment of $BaSO_4$ increased the thermal stability of the composites	[23]

(continued)

Table 1 (continued)

Fibre	Matrix	Thermal Properties	References
Curauá	Polyester	The addition of the fibre and chemical treatment of fibres with NaOH improved the thermal stability of the composites	[26]
Mulberry	Polyester	The thermal stability of the composites increased by increasing the NaOH concentration	[27]
Jute + Oil palm	Epoxy	The hybridization of the composites increased the maximum degradation temperature when compared to the pure Oil palm composite	[13]

3 Differential Scanning Calorimetry (DSC)

The DSC determines the material transitions. The thermal phase change of the composites is shown [28, 29].

The T_g is a vital material property when considering the biocomposites for a particular end-use application. It is well known that the "normal" state of most thermoset polymers at room temperature is rigid (amorphous solid). Below the T_g, the molecular chains of the thermoset resins do not present enough energy to let them move around (the molecules are frozen in place as a rigid structure because of the short-chain length, molecular groups separating off the chain and interlocking with each other). Moreover, when the polymer resin is heated, the molecules of the polymer resin gain energy and they can start to move around. The amorphous rigid structure of the thermoset polymer resin is transformed to a flexible structure (rubbery state) when a certain heat energy level is attained, and the polymer molecules are allowed to move freely around each other.

To conclude, the service temperature of polymer resins should always be below the T_g. If the composites are used above their T_g, they will quickly lose their mechanical properties (strength and stiffness), and they will continue to maintain some mechanical properties until the temperature reaches T_m. The crystallization temperature (T_c) is associated with the point where polymer chain alignment modification is possible. Upon reaching the T_c, ordered crystalline chain regions appear, called lamellae. However, amorphous regions remain in the structure.

It should be noted that the crystallization is an exothermic peak in a DSC curve. T_c temperature is higher than T_g but still lower than the melting temperature (T_m). Finally, the melting temperature (T_m) is when the polymeric chains lose their bonds and turn into a liquid. This process is called endothermic transition. In general, T_m for a thermoset polymer is higher than its T_g. At temperature above T_g but below T_m, the polymer resin is in a rubbery state, and the material can exhibit large deformation under a relatively low load.

The DSC technique was utilised by several researchers to test the thermal stability of bio composites. [17, 26, 30–35]. Teixeira et al. [26], used the DSC method to investigate the effect of several chemical treatments on the thermal characteristics of curauá fibre polyester based composites. Different types of chemical treatments were used: 10% of barium hydroxide Ba(OH)2 for 48 h at 25 °C, 14% of calcium hydroxide Ca(OH)2 for four h at 70 °C, 10% of potassium hydroxide (KOH) for one h at 25 °C, 5% of sodium hydroxide (NaOH) for two h at 70 °C and 5% of silane (Trimethoxy(propyl) for four h at 25 °C. It was found that the chemical treatment increased the T_g of the treated composite when compared to untreated. Furthermore, the study reports that the chemical treatment of calcium hydroxide (Ca (OH)2) provide a T_g of 141.2 °C for the treated composites, compared to the 133.69 °C obtained for the untreated composite. The authors state that this increase in T_g was due to an improvement in the interaction.

Souza et al. [30] studied the percentage of fibre on the thermal characteristics of biocomposites reinforced with caranan fibre. The studied variation of fibre/matrix percentage was 0 to 30%. The authors show that the increase of the caranan fibre increases the T_g of the composites. The fibre content with 20% and 30% had a *Tg* value of 96 °C and 113 °C, respectively.

Bhoopathi et al. [32] studied the effect of eggshell nanoparticles on the thermal properties of hemp reinforced composites. The natural fibres were treated by mercerization (5% of NaOH for five h at room temperature). The studied cases were: Hemp without eggshell (0%ESP), hemp + 7% eggshell (7%ESP), hemp + 14% eggshell (14%ESP), hemp + 21% eggshell(21%ESP). When compared to unmodified composite samples, the authors found that raising the nanoparticle proportion boosted the thermal properties of composites. The best-case found was the 14%ESP, where the maximum exothermic peak value of degradation temperature onset was 411.6 °C, while for the unfilled case, it was 326.2 °C.

Gupta et al. [31] used the DSC technique to study the thermal properties of jute/sisal fibres in epoxy-based composites. The studied cases were: jute (J1), sisal (S1), 50% of jute + 50% of sisal (H1), 25% of jute + 75% of sisal (H2) and 75% of jute + 25% of sisal (H3). The composites were manufactured using the hand-lay-up technique and total fibre loading of 30%wt. The values of T_g found for H1 samples was 73.86 °C, for the H2 case was 72.86 °C, while for H3, the T_g value found was 68.36 °C when compared with the T_g of the matrix (65.16 °C).

Pereira et al. [17], used DSC to investigate the influence of hybridisation on the thermal properties of pure sisal and epoxy hybrid composites. Figure 6 shows the DSC curves for the composites studied. It can be seen that two events predominate, endothermic and exothermic, around 100 °C and 375 °C, respectively. Sisal + curauá was the sample that absorbed the most heat in the endothermic event and the least released heat in the exothermic event.

Sumesh et al. [33] investigated the thermal properties of pineapple (P)/Flax(F) reinforced epoxy-based composite. The microfilters were extracted by peanut oil cake. The percentages of CMF were 1 to 3% and treated by mercerization (4% of

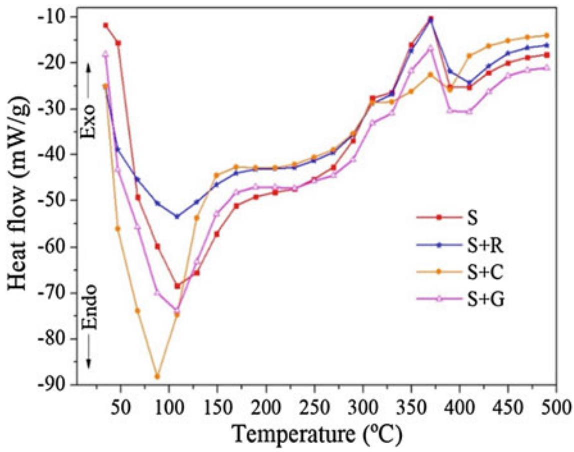


Fig. 6 DSC curves of epoxy sisal-based composites function as a hybridization (S-Sisal; S + R- Sisal + ramie; S + C-Sisal + curauá and S + G- sisal + glass fibre). Reproduced with permission from authors of Pereira et al. [17]

NaOH with 80 °C for 1.5 h). The natural fibres of pineapple and flax were treated using the mercerization treatment (5% NaOH for three h), and 30 and 35% wt of reinforcement were used in the hybrid composites. The manufacturing process used was compression moulding. The studied cases were: 30 wt% PF/0%CMF, 30 wt% PF/1%CMF, 30 wt% PF/2%CMF, 30 wt% PF/3%CMF and 35 wt% PF/0%CMF, 35 wt% PF/1%CMF, 35 wt% PF/2%CMF, 35 wt% PF/3%CMF. In addition to untreated cases, the untreated 30 wt% PF/2%CMF and untreated 35 wt% PF/3%CMF were studied. The results found indicate that for the case of 30%wt, the percentage of 2% CMF shows the higher endothermic peak with a value of 114.94 °C and enthalpy of 499.39 Jg^{-1}. For the case of 35%wt, the percentage of 3%CMF had an endothermic peak value of 120.39 °C and enthalpy of 504.21 Jg^{-1}. The authors indicated that untreated composite presented lower thermal properties when compared to the treated composite cases. Table 2 summarizes the results from numerous modern researches on the thermal properties of bio fibre.

4 Dynamic Mechanical Analysis (DMA)

DMA determines the following thermal data: storage modulus (*E*'), loss modulus (*E*"), glass transition temperature (T_g) [39], and damping factor ($tan\ \delta = E''/E'$). The storage modulus (*E*') is associated with the energy storage of the elastic characteristics of the material [34, 40, 41]. It has also been linked to the composites sample's "stiffness" [40, 41]. The loss modulus (*E*) is linked to the energy dissipation promoted by the viscous part of the composite sample. This dissipation is related to the internal molecular friction of the molecular chain for the following reasons: morphological transformation and relaxation, morphological and system heterogeneity [10, 41]. Damping factor It is calculated by dividing the storage modulus and loss modulus ($tan\ \delta = E''/E'$), and is related to the internal mobility of polymer molecular chains,

Table 2 Bio fibre composites: Thermal properties by DSC analysis

Fibre	Matrix	Thermal Properties	References
Curauá	Polyester	The chemical treatments used increased the T_g of the composites. The best treatment was Ca $(OH)_2$ with a T_g value of 141.92 °C	[26]
Jute + ZrO_2	Polyester	The presence of the nano filler increased the T_g of the composite	[35]
Jute + ramie	Epoxy	Alkalization and mixed (alkalization + silane) treatment increased the thermal properties	[34]
Caranan	Epoxy	The endothermic peak shows a large amount of water retained in the fibre	[30]
Jute + sisal	Epoxy	The addition of natural fibre produced an increase of thermal properties (T_g and T_c)	[31]
Hemp + eggshell	Epoxy	The incorporation of filler reduced the exothermic peak of the composite	[32]
Flax + Pineapple + Micro Cellulose (CMF)	Epoxy	The addition of CMF improved the endothermic peak and enthalpy when compared to the unmodified composite	[33]
Kenaf + Sisal	Bio-Epoxy	UV aging increased the T_g of hybrid composites and pure fibres	[36]
Jute + coir	Epoxy	The endothermic peak showed water loss between 60–120 °C	[37]
Flax + TiO_2	Epoxy	The addition of 0.7% of nano filler increased the T_g by 5 °C when compared to the unfilled composite	[38]

indicating the influence of fiber/matrix interaction [34, 41, 42]. Due to the quality of the fiber/matrix interaction, a high *tan* δ value means that the system consumes more energy than it stores. On the other hand, a low *tan* δ value indicates that the polymer chain is less fluid, indicating that the fiber/matrix interface contact is appropriate.

Several different test technique setups are possible in the DMA analysis. However, the three-point bending mode is the most popular test method for composite materials because it eliminates the mixed loading seen in single and double cantilever modes and generates quantifiable stresses in reasonably rigid materials. Depending on the methodology used, the glass transition temperature variation for a given material may be reported via the DMA analysis (up to 25 °C). The calculation method may also be more or less conservative, taking the T_g via first inflexion point/modulus drop onset or the *tan* δ peak, respectively [43].

The presence of fillers, fibre content and orientation, and chemical treatment of the fibres have all been proven to alter the dynamic mechanical properties of composite materials in the literature [41, 44, 45]. The testing mode also influences the DMA test results.

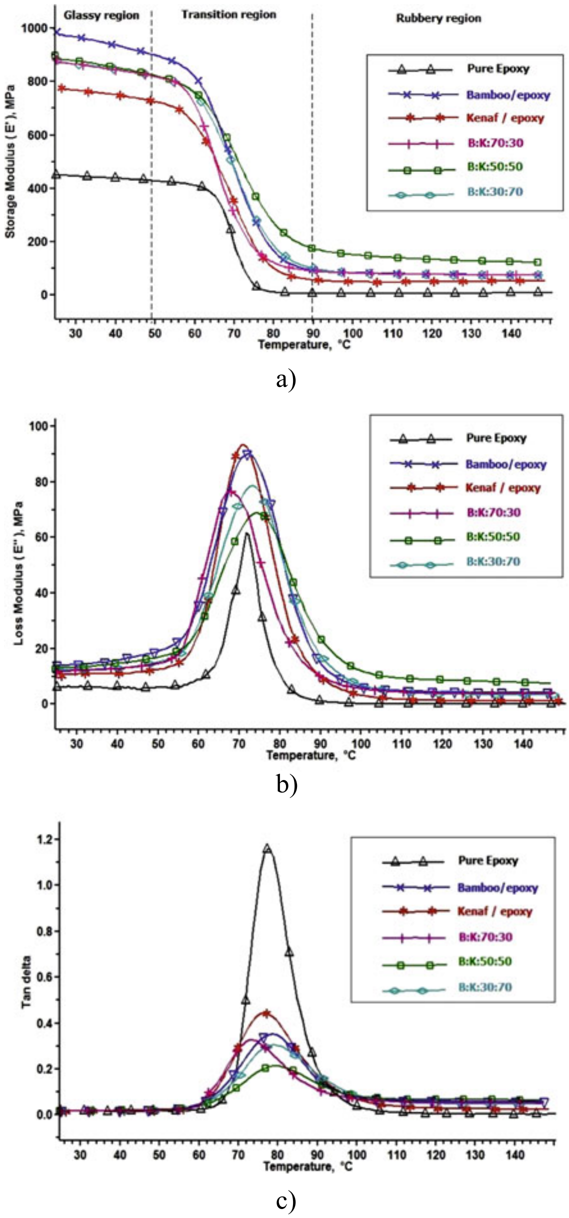
The DMA analysis was used by several researchers to determine the thermal properties of bio fibre composites [20, 27, 31, 34, 36, 46, 47]. For example, Yorseng et al. [36] analyzed the effect of natural kenaf/sisal hybrid composites' accelerated weathering on bio-epoxy resins. The configurations studied were: Kenaf (KKK), Sisal (SSS) and Kenaf + Sisal (KSK and SKS). The exposure time was 555 h with interleaved UV and water spray cycles. They state that the degradation process showed an increase in thermal properties for all cases studied. The incorporation of fibres (sisal and Kenaf) did not affect the glass transition (T_g) of the composites. Moreover, the hybridization of natural fibres increased the storage modulus values (E') compared to pure resin.

Shanmugasundaram et al. [27], estimated the effect of alkalinization treatment on the mechanical and thermal properties of mulberry reinforced polyester-based composites. The studied composites were: untreated mulberry fibre composite (UTMF) and Akali treated mulberry fibre composite. It was found that the 10% ATMFC samples presented higher values of storage modulus and loss modulus compared to the other cases studied.

Kumar et al. [46], used the DMA analysis to investigate the thermal properties of bio fibre composites. The studied cases were: Flax (F), Ramie (R) and Flax + Ramie (F + R). The value of E' found for the hybrid composite was 9.03GPa, whereas, for the pure resin, the value of the storage modulus (E') was 1.84 GPa, showing that the hybridization increased the viscoelastic properties of the composite. The highest T_g value was reported for the hybrid composite (110 ºC), while for the flax, ramie and bio epoxy cases, the reported values were 91 °C, 95 °C and 80 °C, respectively. It was found that the hybridization technique resulted in a higher number of polymer chains, increasing the dissipation of energy of the composite, positively affecting the glass transition temperature.

Chee et al. [48] used the Thermomechanical analysis (TMA) and DMA analysis to investigate the effect of hybridization of bamboo (B) and kenaf (K) fibres on the thermal properties of various configurations in epoxy resin-based hybrid composites. The authors reported that the composite with 100% Bamboo obtained a value of storage modulus (E') of 979 MPa, while the epoxy resin and 100% Kenaf had 449 and 775 MPa, respectively. Figure 7a shows that the storage modulus values of hybrid composites were between the values of composites reinforced by kenaf and bamboo fibres. The loss modulus (E") curves showed that the hybrid composite Kenaf (50%) + Bamboo (50%) presented a T_g of 74.24 °C, while for the 100% Kenaf composite, the T_g value was70.85 °C (see Fig. 7b). It was also shown that fibre incorporation increases the peak width of the loss modulus (E"). The weight ratio of 50:50 of the bamboo fibre to kenaf fibre was the ideal mixing ratio which presented improved thermomechanical and dynamic mechanical properties. The authors state that this indicates effective stress transfer and improved interfacial interaction between fibre and matrix. Figure 7c shows that the neat epoxy resin had the highest $tan\ \delta$ peak

Fig. 7 Representative curves for the DMA test results of epoxy resin and hybrid epoxy composites **a** Storage modulus (*E*') and **b** Loss modulus (*E*"), **c** Tan delta versus temperature. Reproduced with permission from [48]



value (1.15), indicating that the system presented increased molecular mobility with more energy dissipation and other vicious behaviour. Lower molecular mobility was linked to the interlocking among fibres and the polymer matrix once fibres were added, which lowered the *tan δ* peak.

Ramakrishnan et al. [47] analyzed the effect of the chemical treatment and incorporating nano-clay in jute reinforced epoxy-based composite. The thermal properties were analyzed using the DMA. The natural fibres were treated with 2.5%, 5% and 7.5% de NaOH. The composites were modified with different percentages of nano-clay: 1, 3, 5 and 7% wt. The studied cases were: untreated jute: 2.5% NaOH treated jute composite, 5% NaOH treated jute composite, and 7.5% NaOH treated jute composite. It was found that the nano-clay modified jute composites presented higher *E*', *E*" and *tan* δ values. The composites modified with 5 wt.% of nano-clay had improved viscoelastic properties. 5% treated jute fibres composites presented highest E' and E'' value but the lowest *tan* δ value. This was explained by the improved interfacial bonding provided by the chemical treatment of the bio fibres.

Table 3 summarizes the results from researches on the thermal properties of bio fibre composites obtained through DMA analysis.

Table 3 DMA study revealed the thermal characteristics of biocomposites

Fibre	Matrix	Thermal Properties	Ref
Jute + sisal	Epoxy	The storage modulus (*E*') of composites was raised through hybridization. Furthermore, when compared to pure jute composite, the T_g of hybrid composites was lower	[31]
Pineapple + kenaf	Phenolic	The treated pineapple fibre increased the T_g of the composites	[20]
Mulberry	Polyester	Treatment with 10% of NaOH increased the storage modulus (*E*') of the composite. The fibres decreased the T_g (values of 69 °C was found the neat resin and 63 °C was found for the untreated composites, respectively	[27]
Aloevera /Hemp/Flax	Epoxy	The hybridization and chemical treatment ($BaSO_4$) increased the storage modulus (*E*') and T_g of composites	[49]
Kenaf + Nanofiller	Epoxy	The incorporation of nanofiller improved the T_g of the composites	[50]
Kenaf + Sisal	Bio-Epoxy	The storage modulus decreased as a function of temperature	[36]
Flax + ramie	Bio-Epoxy	Hybrid composites at 30% weight fraction of fibresprovided best results with maximum storage (9.03 GPa), loss modulus (1.45 GPa), and maximum T_g (110 °C)	[46]

(continued)

Table 3 (continued)

Fibre	Matrix	Thermal Properties	Ref
Jute + Nanoclay	Epoxy	The nano-clay modified jute composites presented higher E', E'' and *tan* δ values. The composites modified with 5 wt.% of nano-clay had improved viscoelastic properties 5% treated jute fibres composites presented highest E' and E'' value but the lowest *tan* δ value. Chemical treatment with 5% NaOH + 5wt% nanoclay provided higher storage modulus and T_g	[47]
Bamboo + Kenaf + Nanoclay	Epoxy	The addition of the nanofiller improved the storage modulus, loss modulus and *tan* $\delta$when compared to the other hybrid composite	[51]
Ramie + Buriti	Polyester	The ramie reinforced composite treated with 2% de NaOH presented higher storage modulus and loss modulus compared to the other treated cases	[18]
Jute + Oil palm	Epoxy	High oil palm to jute fibre ratio lowered the storage modulus. Loss modulus presented an increasing trend as a function of increasing jute fibre content	[13]
Bamboo + Kenaf	Epoxy	The complex and storage modulus of bamboo composite are higher compared to kenaf composite. Hybrid composites value lie between bamboo and kenaf composites	[48]

5 Conclusions

Thermal analysis can provide helpful information for developing new materials and optimising the selection process of these materials for new applications. The weight loss %, the deprivation of temperature, T_g, and viscoelastic properties are the literature's most commonly researched thermal properties. The thermal properties of bio fibre composites are influenced by a number of factors. For example, the kind of fibre and matrix, the presence of additives and fillers, fibre content, fibre origination, chemical treatment of the fibres, manufacturing process, and loading type. It is critical to make sure the bio fibres used in composites can resist the heat generated during the fabrication process and preserve their properties after that. Different approaches were used in the literature to enhance the thermal properties of bio fibres based composite materials. Using natural fibres with low lignin content, for example, improves the thermal performance of composites. Another approach is removing lignin through fibres treatment. Finally, adding synthetic fibres or fillers to natural fibre reinforced composites improves their thermal stability.

References

1. Banea MD, Da Silva LFM (2009) Adhesively bonded joints in composite materials: An overview. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 223(1):1–18. https://doi.org/10.1243/14644207JMDA219
2. Budhe S, de Barros S, Banea MD (2019) Theoretical assessment of the elastic modulus of natural fiber-based intra-ply hybrid composites. Journal of the Brazilian Society of Mechanical Sciences and Engineering 41 (6). doi:https://doi.org/10.1007/s40430-019-1766-z
3. Banea MD, Neto JSS, Cavalcanti DKK (2021) Recent Trends in Surface Modification of Natural Fibres for Their Use in Green Composites. In: Thomas S, Balakrishnan P (eds) Green Composites. Springer Singapore, Singapore, pp 329–350. doi:https://doi.org/10.1007/978-981-15-9643-8_12
4. Wambua P, Ivens J, Verpoest I (2003) Natural fibres: can they replace glass in fibre reinforced plastics? Compos Sci Technol 63(9):1259–1264
5. de Queiroz HFM, Banea MD, Cavalcanti DKK (2021) Adhesively bonded joints of jute, glass and hybrid jute/glass fibre-reinforced polymer composites for automotive industry. Applied Adhesion Science 9 (1). doi:https://doi.org/10.1186/s40563-020-00131-6
6. Pereira AL, Banea MD, Pereira AB (2020) Effect of intralaminar hybridization on mode I fracture toughness of natural fiber-reinforced composites. Journal of the Brazilian Society of Mechanical Sciences and Engineering 42 (9). doi:https://doi.org/10.1007/s40430-020-02525-w
7. de Queiroz HFM, Banea MD, Cavalcanti DKK (2020) Experimental analysis of adhesively bonded joints in synthetic- and natural fibre-reinforced polymer composites. J Compos Mater 54(9):1245–1255. https://doi.org/10.1177/0021998319876979
8. Asim M, Jawaid M, Paridah MT, Saba N, Nasir M, Shahroze RM (2019) Dynamic and thermo-mechanical properties of hybridized kenaf/PALF reinforced phenolic composites. Polym Compos 40(10):3814–3822
9. Krishnasamy S, Thiagamani SMK, Kumar CM, Nagarajan R, Shahroze R, Siengchin S, Ismail SO, MP ID, (2019) Recent advances in thermal properties of hybrid cellulosic fiber reinforced polymer composites. Int J Biol Macromol 141:1–13
10. Asim M, Paridah MT, Chandrasekar M, Shahroze RM, Jawaid M, Nasir M, Siakeng R (2020) Thermal stability of natural fibers and their polymer composites. Cellulose 174:175
11. Guo Y, Zhu S, Chen Y, Li D (2019) Thermal properties of wood-plastic composites with different compositions. Materials 12(6):881
12. Członka S, Strąkowska A, Kairytė A (2020) Effect of walnut shells and silanized walnut shells on the mechanical and thermal properties of rigid polyurethane foams. Polymer Testing:106534
13. Jawaid M, Khalil HA, Bakar AA, Hassan A, Dungani R (2013) Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites. J Compos Mater 47(13):1633–1641
14. Dalla Libera Junior V, Leão RM, Franco Steier V, da Luz SM (2020) Influence of cure agent, treatment and fibre content on the thermal behaviour of a curaua/epoxy prepreg. Plast, Rubber Compos 49(5):214–221
15. El Boustani M, Lebrun G, Brouillette F, Belfkira A (2017) Effect of a solvent-free acetylation treatment on reinforcements permeability and tensile behaviour of flax/epoxy and flax/wood fibre/epoxy composites. The Canadian Journal of Chemical Engineering 95(6):1082–1092
16. Chin SC, Tee KF, Tong FS, Ong HR, Gimbun J (2020) Thermal and mechanical properties of bamboo fiber reinforced composites. Materials Today Communications 23:100876. doi:https://doi.org/10.1016/j.mtcomm.2019.100876

17. Pereira AL, Banea MD, Neto JS, Cavalcanti DK (2020) Mechanical and Thermal Characterization of Natural Intralaminar Hybrid Composites Based on Sisal. Polymers 12(4):866
18. Lavoratti A, Romanzini D, Amico SC, Zattera AJ (2017) Influence of Fibre Treatment on the Characteristics of Buriti and Ramie Polyester Composites. Polym Polym Compos 25(4):247–256. https://doi.org/10.1177/096739111702500401
19. Rashid B, Leman Z, Jawaid M, Ghazali MJ, Ishak MR (2017) Influence of Treatments on the Mechanical and Thermal Properties of Sugar Palm Fibre Reinforced Phenolic Composites. 2017 12 (1):16
20. Asim M, Paridah MT, Saba N, Jawaid M, Alothman OY, Nasir M, Almutairi Z (2018) Thermal, physical properties and flammability of silane treated kenaf/pineapple leaf fibres phenolic hybrid composites. Compos Struct 202:1330–1338
21. Cavalcanti DKK, Banea MD, Neto JSS, Lima RAA (2020) Comparative analysis of the mechanical and thermal properties of polyester and epoxy natural fibre-reinforced hybrid composites. J Compos Mater 55(12):1683–1692
22. Nimanpure S, Hashmi SAR, Kumar R, Bhargaw HN, Kumar R, Nair P, Naik A (2019) Mechanical, electrical, and thermal analysis of sisal fibril/kenaf fiber hybrid polyester composites. Polym Compos 40(2):664–676. https://doi.org/10.1002/pc.24706
23. Arulmurugan M, Selvakumar AS, Prabu K, Rajamurugan G (2020) Effect of barium sulphate on mechanical, DMA and thermal behaviour of woven aloevera/flax hybrid composites. Bull Mater Sci 43(1):58. https://doi.org/10.1007/s12034-019-2018-7
24. Hidalgo-Salazar MA, Correa JP (2018) Mechanical and thermal properties of biocomposites from nonwoven industrial Fique fiber mats with Epoxy Resin and Linear Low Density Polyethylene. Results in Physics 8:461–467. https://doi.org/10.1016/j.rinp.2017.12.025
25. De Rosa IM, Santulli C, Sarasini F (2010) Mechanical and thermal characterization of epoxy composites reinforced with random and quasi-unidirectional untreated Phormium tenax leaf fibers. Materials & Design (1980–2015) 31 (5):2397–2405. doi:https://doi.org/10.1016/j.matdes.2009.11.059
26. Teixeira LA, Vilson Dalla Junior L, Luz SM (2020) Chemical treatment of curaua fibres and its effect on the mechanical performance of fibre/polyester composites. Plast, Rubber Compos 50(4):189–199. https://doi.org/10.1080/14658011.2020.1862978
27. Shanmugasundaram N, Rajendran I, Ramkumar T (2018) Static, dynamic mechanical and thermal properties of untreated and alkali treated mulberry fiber reinforced polyester composites. Polym Compos 39(S3):E1908–E1919. https://doi.org/10.1002/pc.24890
28. Jesuarockiam N, Jawaid M, Zainudin ES, Thariq Hameed Sultan M, Yahaya R (2019) Enhanced Thermal and Dynamic Mechanical Properties of Synthetic/Natural Hybrid Composites with Graphene Nanoplateletes. Polymers 11(7):1085
29. Veerasimman A, Shanmugam V, Rajendran S, Johnson DJ, Subbiah A, Koilpichai J, Marimuthu U (2021) Thermal Properties of Natural Fiber Sisal Based Hybrid Composites – A Brief Review. Journal of Natural Fibers:1–11. doi:https://doi.org/10.1080/15440478.2020.1870619
30. Souza AT, Pereira Junio RF, Neuba LdM, Candido VS, da Silva ACR, de Azevedo ARG, Monteiro SN, Nascimento LFC (2020) Caranan Fiber from Mauritiella armata Palm Tree as Novel Reinforcement for Epoxy Composites. Polymers 12(9):2037
31. Gupta MK (2016) Thermal and dynamic mechanical analysis of hybrid jute/sisal fibre reinforced epoxy composite. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 232(9):743–748. https://doi.org/10.1177/1464420716646398
32. Bhoopathi R, Ramesh M (2020) Influence of eggshell nanoparticles and effect of alkalization on characterization of industrial hemp fibre reinforced epoxy composites. J Polym Environ 28:2178–2190
33. Sumesh KR, Kanthavel K, Kavimani V (2020) Peanut oil cake-derived cellulose fiber: Extraction, application of mechanical and thermal properties in pineapple/flax natural fiber composites. Int J Biol Macromol 150:775–785. https://doi.org/10.1016/j.ijbiomac.2020.02.118
34. Neto J, Lima R, Cavalcanti D, Souza J, Aguiar R, Banea M (2019) Effect of chemical treatment on the thermal properties of hybrid natural fiber-reinforced composites. J Appl Polym Sci 136(10):47154

35. Biswas B, Sawai P, Santra A, Gain A, Saha P, Mitra BC, Bandyopadhyay NR, Sinha A (2019) Thermal stability, swelling and degradation behaviour of natural fibre based hybrid polymer composites. Cellulose 26(7):4445–4461. https://doi.org/10.1007/s10570-019-02383-3
36. Yorseng K, Rangappa SM, Pulikkalparambil H, Siengchin S, Parameswaranpillai J (2020) Accelerated weathering studies of kenaf/sisal fiber fabric reinforced fully biobased hybrid bioepoxy composites for semi-structural applications: Morphology, thermo-mechanical, water absorption behavior and surface hydrophobicity. Construction and Building Materials 235:117464. doi:https://doi.org/10.1016/j.conbuildmat.2019.117464
37. Saw SK, Sarkhel G, Choudhury A (2012) Preparation and characterization of chemically modified Jute-Coir hybrid fiber reinforced epoxy novolac composites. J Appl Polym Sci 125(4):3038–3049. https://doi.org/10.1002/app.36610
38. Prasad V, Joseph MA, Sekar K (2018) Investigation of mechanical, thermal and water absorption properties of flax fibre reinforced epoxy composite with nano TiO2 addition. Compos A Appl Sci Manuf 115:360–370. https://doi.org/10.1016/j.compositesa.2018.09.031
39. Chandrasekar M, Ishak M, Sapuan S, Leman Z, Jawaid M (2017) A review on the characterisation of natural fibres and their composites after alkali treatment and water absorption. Plast, Rubber Compos 46(3):119–136
40. Lu N, Oza S (2013) A comparative study of the mechanical properties of hemp fiber with virgin and recycled high density polyethylene matrix. Compos B Eng 45(1):1651–1656
41. Saba N, Jawaid M, Alothman OY, Paridah M (2016) A review on dynamic mechanical properties of natural fibre reinforced polymer composites. Constr Build Mater 106:149–159
42. Jawaid M, Khalil HA, Hassan A, Dungani R, Hadiyane A (2013) Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites. Compos B Eng 45(1):619–624
43. Akay M (1993) Aspects of dynamic mechanical analysis in polymeric composites. Compos Sci Technol 47(4):419–423
44. Ashok R, Srinivasa C, Basavaraju B (2019) Dynamic mechanical properties of natural fiber composites—a review. Advanced Composites and Hybrid Materials:1–22
45. Członka S, Strąkowska A, Kairytė A (2021) Coir Fibers Treated with Henna as a Potential Reinforcing Filler in the Synthesis of Polyurethane Composites. Materials 14(5):1128
46. Kumar S, Zindani D, Bhowmik S (2020) Investigation of mechanical and viscoelastic properties of flax-and ramie-reinforced green composites for orthopedic implants. J Mater Eng Perform 29:3161–3171
47. Ramakrishnan S, Krishnamurthy K, Rajeshkumar G, Asim M (2020) Dynamic Mechanical Properties and Free Vibration Characteristics of Surface Modified Jute Fiber/Nano-Clay Reinforced Epoxy Composites. J Polym Environ 29(4):1076–1088. https://doi.org/10.1007/s10924-020-01945-y
48. Chee SS, Jawaid M, Sultan MTH, Alothman OY, Abdullah LC (2019) Thermomechanical and dynamic mechanical properties of bamboo/woven kenaf mat reinforced epoxy hybrid composites. Compos B Eng 163:165–174. https://doi.org/10.1016/j.compositesb.2018.11.039
49. Arulmurugan M, Prabu K, Rajamurugan G, Selvakumar AS (2019) Viscoelastic behavior of aloevera/hemp/flax sandwich laminate composite reinforced with BaSO4: Dynamic mechanical analysis. J Ind Text 50(7):1040–1064. https://doi.org/10.1177/1528083719852312
50. Khan A, Asiri AM, Jawaid M, Saba N, Inamuddin (2020) Effect of cellulose nano fibers and nano clays on the mechanical, morphological, thermal and dynamic mechanical performance of kenaf/epoxy composites. Carbohydrate Polymers 239:116248. doi:https://doi.org/10.1016/j.carbpol.2020.116248
51. Chee SS, Jawaid M, Alothman OY, Fouad H (2021) Effects of Nanoclay on Mechanical and Dynamic Mechanical Properties of Bamboo/Kenaf Reinforced Epoxy Hybrid Composites. Polymers 13 (3). doi:https://doi.org/10.3390/polym13030395

Challenges of Bio Fibre Composites

Dynamic Mechanical Analysis (DMA) of Natural Fibre Reinforced Polymer Matrix Composites (NFRPMC)-Review

T. Rajmohan, D. Vijayan, K. Mohan, S. Vijayabhaskar, and K. Palanikumar

Abstract Natural fibre inclusion in the polymer composites as reinforcement material has achieved rising applications in engineering and technology. Dynamic Mechanical Analysis (DMA) can be considered as one of the useful tools for measuring phase variations in NFRPMCs and damping in terms of time, temperature, frequency, atmosphere and stress. The applications of DMA include pharmaceutical and biomedical science, chemical industry, automotive industry, oil and gas industry. The fibre contents, fibre shape and sizes, orientations, fibre treatment, stacking sequences and type of matrix in the NFPMCs influence DMA. Dynamic loading conditions are often staggered in mechanical systems due to live loads. Therefore, in this paper, extensive source of reported literature concerning DMA of NFRPMCs and the effect of different natural fibres, chemical treatment, fillers, matrix and compositions were examined in detail.

Keywords Natural fibre · DMA · Polymer matrix · Tan δ · Storage modulus · Loss modulus

1 Introduction

Renewable natural fibres are employed in obtaining advanced polymer materials with high-performance. The usage of reprocessed natural fibre scrap as reinforcing material in the polymer composites is an environmental sustainability opportunity [1].

T. Rajmohan (✉)
Centre for Composite Science and Technology, Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya, Enathur, Kanchipuram 631561, India

D. Vijayan · K. Mohan · S. Vijayabhaskar
Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya, Enathur, Kanchipuram 631561, India

K. Palanikumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, West Tambaram, Chennai 600044, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_17

Some of the advantages of natural fibres compared to synthetic fibres are biodegradability, recyclability, renewability, reduced health hazard, less energy consumption, equivalent specific tensile properties, less density, non-skin irritant, nonabrasive to the equipment and economical [2]. Natural fibres are employed in new areas of application due to industrial demands and environmental regulation, in spite of this, the research in this area is still new, and the requirement for additional research is suggested by many researchers [3]. Di Landro and Lorenzi [4] proved that natural fibre composites can be substituted for glass fibre composites in numerous engineering applications with distinct dynamic mechanical properties.

The DMA of composites is more complicated and engages the assumptions of micromechanics and constitutive equations [5]. DMA further rely upon the nature of components, morphology and interface [6]. The researches expound that the testing mode, orientation of fibre, presence of fibre content and filler control the dynamic mechanical properties of composite material [7, 8]. DMA is a dominant analytical mechanism used to characterise to study the material performance that delivers data on substance properties and thermal transitions [9]. DMA is an attractive method considering its user-friendliness and its capability in obtaining huge quantities of experimental data with a smaller number of experiments. The resulting stress of the material is measured due to the oscillatory stress at defined frequencies and temperatures [10]. The dynamic mechanical properties are computed with reference to complex modulus of a component based on the function of dynamic storage and loss moduli. Therefore, DMA measures material deformation resistance including the viscous as well as elastic responses [11]. DMA aids in defining the transformation of phases and tranquillity events in performances of various material combinations. Similarly, DMA found to be a well and useful approach for studying the tranquilities, pertinent tan δ and stiffness in plain polymer and polymers incorporated with fibre [12].

DMA properties are influenced by the hybridisation, chemical treatment of fibres, and difference in frequencies [8]. In DMA, vibrating force is applied on to the sample; sine waves corresponding to the stress–strain curves were noted based on the time. DMA aids in defining the phase metamorphosis and tranquillity events in different combination material performances [13]. The complex modulus in DMA is calculated using the sine wave loading response of the materials (Fig. 1) which corresponds to the fraction of stress and strain given by the Eq. [5]

$$\mathrm{Complex(Young)modulus(E)} = \mathrm{Stress/Strain} \tag{1}$$

$$E = E' + iE'' \tag{2}$$

where, E″ is loss modulus andE' E′ is storage modulus.

The temperature behaviour and load-bearing ability of the composites is the function maximum stored by composites during one oscillation, which is termed as storage modulus E’ obtained from energy equation [5]. From Fig. 1, the response

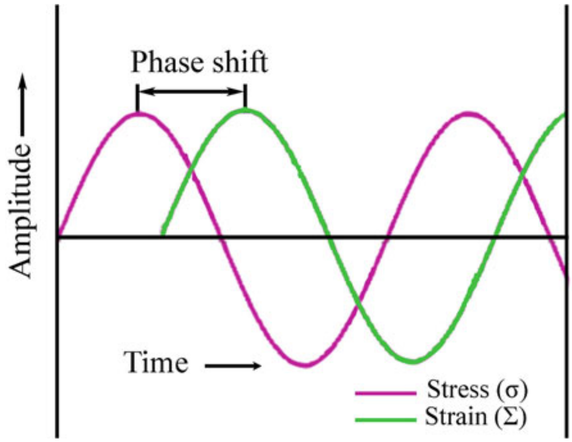


Fig. 1 Response of Sinusoidal oscillation [5]

values for dynamic properties are expressed in terms of E′ and E″. DMA can be used to obtain the material dynamic mechanical properties as follows.

$$E' = ECos\delta \tag{3}$$

The rate of heat energy dispersed during a single sinusoidal load cycle is known as the composite loss modulus or viscous response. The composite dynamic transition temperature can probably be recognised by the peak in E″ curve [5].

$$E' = ESin\delta \tag{4}$$

The composite molecular mobility represented through the relation among E′ and E″ is termed as damping given by[5]

$$tan\delta = E'' \tag{5}$$

where δ-Phase lag, tan δ describes the versatile and non-flexible nature of the material.

Meanwhile, the NFRPMC experiences many forms of dynamic stress throughout the service, investigations on the visco-elastic characteristics of such composites are of excessive rank.

Dynamic mechanical analyser is used to compute the visco-elastic characteristics like tan δ, E′ and E″ in terms of temperature. The dimension of the test sample attached to the twin cantilever clamp is 25 × 10 × 1 0 mm. The test conditions employed are 25 to 350 °C temperature, 5 °C/min heating rate, 50 μm amplitude and 10 Hz frequency [14] (Fig. 3).The availability of the reviews on DMA is few and fair with restricted scope to the authors best awareness [5, 7]. The main aim of this review is to gather all the updated advancements in DMA of natural fibre reinforced composites. The published investigations are summarised in accordance with various

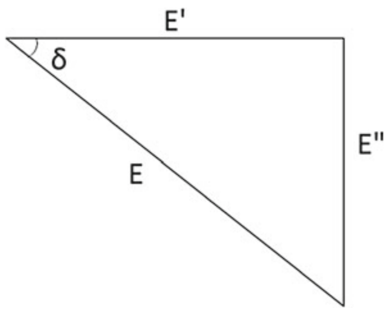


Fig. 2 Complex modulus of DMA [5]

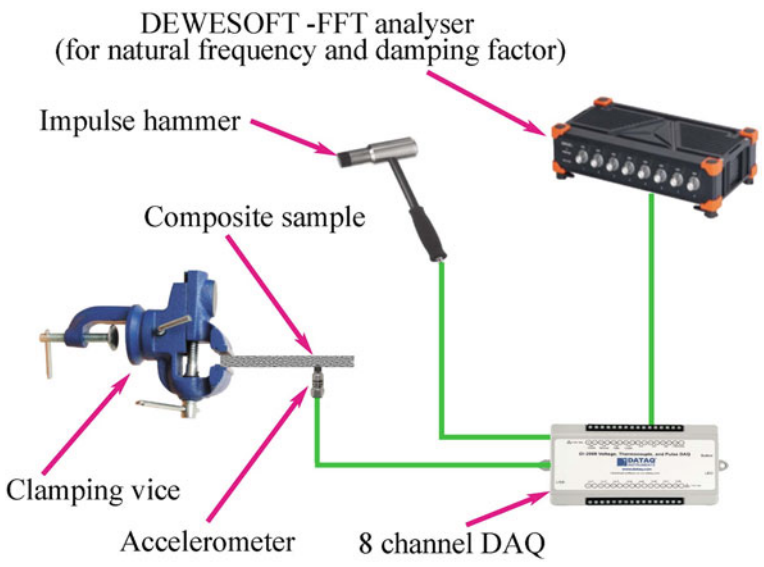


Fig. 3 Free vibration analysis experimental setup [16]

approaches for the improvement of dynamic properties that contain the influences of polymer matrix, fibre and its arrangement, treatment of fibres, dispersed fillers and interfacial region. This study is expected to give practical direction towards the upcoming progress in DMA of composites reinforced with natural fibre.

2 DMA of Thermoplastic Polymer Composites Reinforced with Natural Fibre

Artificial non-biodegradable polymers are usually hired as matrices; some of these, such as polypropylene or some thermosets have met out temperatures well-suited with temperature limits of natural fibres [15]. Fully biodegradable composites are, however, projected to come from the use of biodegradable polymer matrices [16]. The matrix intrinsic viscoelastic damping is considered to be the primary donor of damping in the composite reinforced with fibre [17]. During DMA, it is found that the stresses transmitted by the matrix mainly due to shearing and elongation [18]. The distribution of stress in the path perpendicular to fibre axis is exclusively determined by the matrix damping [19]. The energy degeneracy is attained through stiff hampering behaviour of the polymeric matrix [20]. Most of the researchers stated that damping can be enhanced through growing the volume fraction of matrix at the incidentals of strength and stiffness [21]. Also reported that the post preserving procedure could decline the damping capacity of the matrix, while concurrently surge the stiffness and dimensional accuracy [22, 23]. A robust relationship is further detected among the composite molecular signals and frequency properties, that are ambitious through the rigid damping appeal in the matrix [24].

Polylactic acid (PLA) and its results are presently the most studied matrix for such employment [25]. Relatively higher strength and stiffness are offered by composite laminates based on PLA matrix, compared to PP matrix NFC; this can be partly credited to a better fibre/biodegradable matrix adhesion [26]. The selection of suitable fabrication technique is the initial step in designing the material for thermoplastic material. Melting temperature for various matrix/graphite systems like PEI, PES, PPS, PAS and PEEK were found. Also, solidification temperatures for plain PAS and PEEK were determined. Further, the transition temperatures conform to the differential scanning calorimetry [27]. Generally, PAR/nylon6 islands-in-sea fibres increase the tensile strength of thermoplastic composite so that it is credibly employed in various fields like protective equipment, automotive, sports and so on [28]. The proportional increase in the sisal fibre increases E' of propylene composites reinforced with sisal fibre as the fibres accumulate in the matrix.

Malleated propylene creates the progress in temperature variation and relatively influences the capacity modulus of rubber-reinforced PP wood fibre composites [30]. Geethammaa et al. [31] found that the energy dissipated by natural rubber composites reinforced with coir fibre is higher when the interfacial bonding is poor in comparison with sound interfacial bonding. In DMA of malleated polyethylene treated HDPE composites reinforced with jute fibre exhibited enhanced storage-loss modulus ratio and damping factor in comparison with untreated composites[21]. Several significant published research on dynamic mechanical analysis of NFRPMC were presented in Table 1[8, 21, 31–37].

Table 1 Some reported research work on DMA of thermoplastic composite materials

Thermoplastic	Natural fibre	References
Polypropylene	Wood	[35]
	Jute	[36]
	Hemp	[37]
	Pineapple leaf	[38]
Natural rubber	Oil palm	[39]
	Coir rubber	[40]
High-density polypropylene	Kenaf	[41]
	Jute	[42]
Low-density polypropylene	Oil palm	[43]

3 DMA of Natural Fibre Reinforced Thermoset Polymer Composites

The measurement of DMA properties of thermoset polymer matrix composites include reduction in stress/creep, superposition temperature, physical aging time, frequency, modulus and glass transition temperature [38]. Dry thermoset DMA properties are demonstrated in Fig. 1. Three areas namely glassy, transition and rubbery plateau can be identified from the Fig. 4. The glassy region is categorised by very low tan δ, low loss modulus and very high storage modulus. Further the transition region has maximum tan δ and loss modulus with 10 – 100 factors decline in storage modulus. The rubbery plateau region contains low tan δ and loss modulus and the crosslink density result in constant storage modulus [39]. A few selected literatures related to the investigations on DMA of thermoset polymer matrix composites was presented in Table 2. Most of the authors have shown that the highly crosslinked

Table 2 A few reported researches on DMA of Thermoset composite materials

Name of fibre	Thermoset polymer	References
Glass	Epoxy	[44]
Jute		[45]
OPEPF		[46]
Sisal		[47]
Jute/kenaf	Polyester	[48]
Glass/ramie		[49]
Pineapple		[50]
Kenaf/hemp		[51]
Eucalyptus wood cellulose fibre	Phenolic	[52]
Jute fibre treated with alkali and untreated	Vinyl-ester	[53]

thermoset polymer with higher stiffness and rigid network arrangement possesses higher storage and loss and modulus whereas significantly lesser loss and storage modulus for light crosslinked polymer [10, 38–46].

4 DMA of Natural Fibre Reinforced Polymer Composites

The acceptance of natural fibre-based biocomposites is mostly attributed to a growth in pollution and eco-friendly issues. Natural fibres are abundantly available with realistic mechanical properties at a lower cost [47]. Investigations pertaining to the composites with natural fibres have improved aggressively owing to the environmental threats posed by the composites based on synthetic fibres [48]. The dynamic properties of NFRPMC depend on surface treatments, fibre modification process, chemical composition, morphology and structure of fibres [49]. Nearly every natural fibre such as coconut sheath, pineapple leaf branches, jute, hemp, sisal, etc., can be applied as reinforcement materials which form proper bonding with the matrix materials [7]. Most researchers proved that the storage, loss modulus and glass transition temperature being greatly affected by the percentage of fibre content layering sequences, chemical treatment of fibres and hybridisation. A few selected literatures related to the effect of fibres on DMA of NFRPMC were presented in Table 3 [57–76].

5 DMA of Chemically Treated NFRPMC

Polymer matrix composite materials commonly suffer from the absence of a matrix-fibre bond which can be fixed by fibre surface modification. Treating chemically or compatibilization by adding third phase between matrix and fibre is considered to be positively useful in refining the interfacial properties of several polymer composite structures [1]. The natural fibre is not useful in its own form due to the presence of foreign particles, dust and undesirable celluloses. Thus, every natural fibre requires a pre-treatment which consists of heating the fibre for a specific duration or cleaning with pure water or soaking in any chemicals. The undesirable cellulose in the fibre can be removed by these treatments, thus improving the strength and making it highly suitable for the resin bonding [14]. Various other chemicals are used by the researchers besides maleic anhydride and alkali. To name a few, esters, silanes, benzoyl chloride, hydrogen peroxide, potassium hydroxide, etc. [62]. The treatment of fibre surface acts as a major factor in the optimization of mechanical characteristics in order to change the damping behaviour proportionately. Various surface treatment processes like coating the reinforced fibre with viscoelastic polymer can enhance the damping properties of such composites effectively [57]. Hence, higher importance is given to the interface characterisation. The alkali treatment improves the properties of composites by decreasing the fibre pull-out, increasing matrix-fibre interfacial bonding and surface impurities of fibre [63].

Table 3 Some of the reported research work on DMA of NFRPMCs

S. no	Natural fibre used	Treatment method	Matrix used	Inference	References
1	Banana–glass	-	Polyester	The E' and E'' values showed 3.5 GPa and 0.19 GPa respectively with addition of four layers	[57]
2	Jute	cyano-ethyl	Polyester	Notable drop in tan δ peak	[58]
3	Kenaf	silane	PLA	E' was doubled compare to unsaturated fibre composites	[59]
4	Wood	–	PLA	Damping properties was improved up to 66% of experimental value	[60]
5	Kenaf, Hemp, flax and glass		Polypropylene	The damping properties of natural fibre at higher compression limits are superior when compared to glass fibre	[61]
6	Kenaf		HDPE	E' and $E''$was improved up to 16.15 GPa and 625 MPa respectively with a 17.5% fiber	[62]
7	Coconut sheath/clay	NaOH and silane	Polyester	$E'$and natural frequency was improved up to 1.75GPa and 44 Hz respectively with silane treated conditions	[63]
8	Palmyra palm leaf stalk-Jute	NaOH	Epoxy	E' of hybrid composites is improved with increment in the jute fibre proportion	[64]

(continued)

Table 3 (continued)

S. no	Natural fibre used	Treatment method	Matrix used	Inference	References
9	Jute–EFB	NaOH	Polyester	E' and E'' were enhanced up to 3.8 MPa and 2.95 MPa respectively as a result of decreased water affinity characteristic of the fibre	[65]
10	Sisal-bagasse	–	Epoxy	Remarkable tan δ and fundamental frequency is 1.15 times as compared to conventional composites	[66]
11	Celluloses microfibres		Poly (ethylene-co-vinyl acetate	The fiber loading results in increased storage modulus and decreased stiffness and damping simultaneously	[67]
12	Jute	NaOH	Vinyl ester-resin	Values increases and decreased in the tan delta with increase in jute fibre content	[68]
13	Sansevieria cylindrical		Polyester matrix	The increase in fibre loading and fiber length influences damping, E' and E'' significantly	[69]
14	Wood flour		Polypropylene	The presence of maleic anhydride–grafted polypropylene decreases the loss factor and improves storage modulus	[70]

(continued)

Table 3 (continued)

S. no	Natural fibre used	Treatment method	Matrix used	Inference	References
15	Pineapple leaf-jute/glass	NaoH	Polyester	The storage modulus decreases as the temperature increases. The alkali treatment of the fibres and inclusion of jute fibres to pineapple leaf improve the storage and loss modulus of hybrid composites	[71]
16	Ramie -jute fiber		Polylactic acid	The temperature increment from 30° to 60 °C decreases E′ to 100 Mpa from 4000 Mpa for all samples while E″ increases to 800 Mpa from 400 Mpa when the temperature increases from 40 °C to 60 °C	[72]
‘17	Palmyra palm leaf stalk-jute fiber	NaoH	Polyester	E′ of hybrid composites is improved with increment in the jute fibre proportion	[73]
18	Glass fiber and Pennisetum purpureum grass fiber	NaoH	Epoxy	E′, E″ and tan δ of composites treated with 5% alkali recorded highest value of 4000 Mpa, 460 Mpa and 0.95 respectively	[74]
19	Jute yarn and banana yarn	Saline, benzoyl chloride, potassium permanganate and alkali (NaOH)	Epoxy	DM characteristics has enhanced with benzoyl chloride and NaOH treatment	[75]
20	Sisal fibers	–	Polystyrene	The increase in temperature decreases E′ while 10% increment of Sisal Fiber in the composite improves E′ by 9.2 Pa	[76]

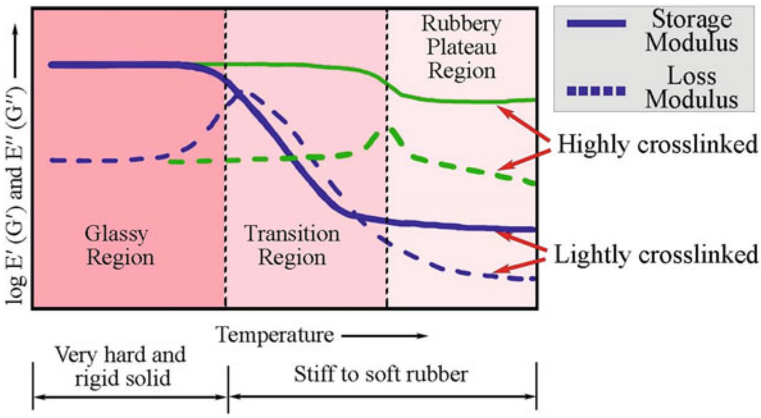
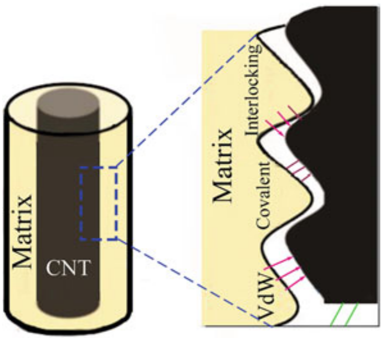


Fig. 4 Schematic representation of DMA of thermosets

Finegan and Gibson found that the coated fibre enhanced the damping behaviour of composites [64]. Aziz and Ansell presented that the composites reinforced with treated kenaf and hemp fibre contain greater storage modulus than the untreated samples. Geethamma et al. concluded that composites with untreated fibres exhibit with poor interfacial bonding. Herrera et al. have noticed that the shear behaviour of composites reinforced with natural fibre were affected by chemical treatment [31]. The storage modulus has been improved in the polypropylene composites using treated jute fibre as shown by Doan et al. [33, 65]. Hossain et al. showed that surface-modified jute-biopol nanophase green composites exhibit better tensile behaviour than untreated fibres reinforced composites [66]. The dynamic mechanical characteristics of pultruded kenaf fibre reinforced composites was greatly influenced by the water absorbed in the samples [67]. Mylsamy and Rajendran resolved that untreated continuous Agave fibre reinforced epoxy composites dissipate higher energy due to weak interfacial bonding [68]. Most of the researchers have proved that the E″ and tan δ values increased with alkali-treated fibre at all frequencies implying improved impact behaviour following the treatment.

Fig. 5 Interfacial interactions between carbon nanotubes and polymer



6 DMA of Nanoparticles Filled NFRPMC

The energy dissipation is improved through the large interfacial area offered by the incorporation of nanoparticles. Figure 5 shows the interfacial interactions between carbon nanotubes and polymer. The interfacial area properties about the included fillers are unique when compared with the bulk matrix [69]. The addition of mica results in reduced modulus and tensile strength [70]. The damping is enhanced more effectively by exfoliated graphite in comparison with nanoclay, SiC and carbon nanotube [71]. The inclusion of nanoclays transfers the composite glass transition temperature to regions with high temperature [72]. The growth of nanowire on the surface of fibre can enhance damping and flexural rigidity properties [73]. Frictional sliding through the interface of epoxy/carbon nanotube is beneficial towards improving energy dissipation [74]. The decrease of the composites damping due to the addition of nano graphite platelets is due to the decrease in porosity [75]. The internal damping can be enhanced by dispersing the nanoscale fillers into E-glass fibre and matrix in hybrid composites [76]. The addition of filler enhances the storage modulus and tensile properties [77]. The composite loss factor increases through the increment of shape memory alloy filler contents [78]. The dissipation of energy is mainly influenced by the filler matrix interface [79]. The carbon nanotube addition in the nanocomposites consistently increases the loss factor and dynamic loss modulus together [80].

The loss modulus decreases by the contribution of filler volume fraction increase [81] and accumulation of smaller particles towards interfacial region results in more twisted path for cracks at the interface [82]. Reducing the size of re mud particle is beneficial to increase damping [83]. A weak interface bonding condition due to the incorporation of coal ash results in better damping performance [84]. The damping decreased with the incorporation of the fly ash cenospheres [85]. The introduction of hollow glass microsphere can enhance damping [86].

The detailed reviews proved that the integration of secondary dampers into matrix had enhanced the energy dissipation potential of NFRPMC. Moreover, the damping performance of composites reinforced with fibre can capably be improved by adding the nanoparticles in interfacial area. The mechanism can be recognised for the declination in interfacial area bond and large cut off damages. Hence, the nanoparticles inclusion is a competent way of getting better damping and capable applications.

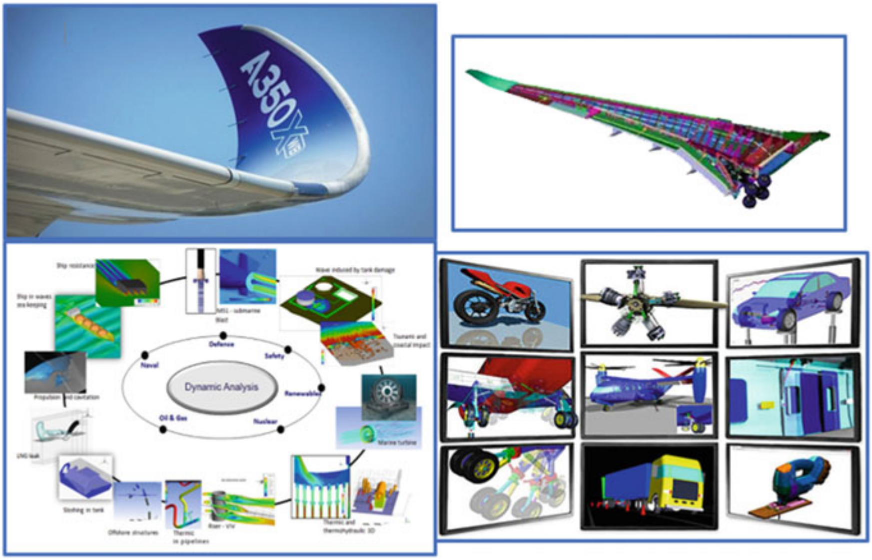


Fig. 6 The application of DMA in various industries [17]

7 Future Trends

Based on the reviews, it is evident that the dynamic behaviour of polymer composites reinforced with natural fibre is equivalent to a range of polymer composites reinforced with different fibres and fillers [1]. Their behaviours are expected and can be calculated using conventional techniques. DMA analyses can shape the dynamic characteristics of composites reinforced with natural fibre, and these results will be of interest to several scientific communities and industries. The inclination towards the usage of composites reinforced with natural fibre is promising, particularly in automobile, infrastructure, and sport goods industries and their market share continue to grow. The need to additional characterise the NFRPMCs in terms of materials properties and design requirements will continue to grow [14]. Determination of the influence of humidity, hygrothermal conditions, thermal cyclical, hazardous chemicals, as well as impact and shock loading on the dynamic behaviour remains necessary to safely design the composites reinforced with natural fibre for various applications (Fig. 6) [7].

8 Conclusions

The present study reviewed several literatures on the DMA of NFRPMCs, including the effect of different natural fibres, chemical treatment, fillers, matrix and compositions. The major conclusions obtained are as follows.

- The DMA is a powerful means to generate information provided for the product development that describe the dynamic characteristics of NFRPMCs.
- DMA method permits in sensing the relief modes and transition of phases in various types of materials to identify the behaviour of material covering an extensive range of temperature and frequencies.
- Most of the researchers stated that the matrix volume fraction increase could improve the damping at the incidentals of strength and stiffness.
- Highly cross-linked thermoset polymer with higher stiffness and rigid network arrangement possesses higher storage and loss and modulus whereas significantly lesser loss and storage modulus for light crosslinked polymer.
- Storage modulus, loss modulus and glass transition temperature were greatly affected by the percentage of fibre content layering sequences, hybridisation and chemical treatment of fibres.
- E'' and tan δ values increased with alkali-treated fibre at all frequencies implying improved impact behaviour following the treatment.
- The integration of secondary dampers into matrix had enhanced the energy dissipation potential of NFRPMC. Moreover, the damping performance of composites reinforced with fibre can capably be improved by adding the nanoparticles in interfacial region.
- Forthcoming work will focus on the manufacturing of entirely green composite and biodegradable polymer nanocomposites reinforced with natural fibre containing enhanced dynamic thermal properties.

Symbols and Abbreviations

Benzoyl chloride	C_7H_5ClO
Damping factor	tan δ
Dynamic Mechanical Analysis	DMA
HDPE	High Density Polyethylene
Loss modulus	E''
Natural Fibre Reinforced Polymer Matrix Composites	NFRPMC
Polylactic acid	PLA
Potassium permanganate,	$KMnO_4$
Saline	SiH_4
Sodium hydroxide	NaOH
Storage modulus	E’

References

1. Rajmohan T, Vinayagamoorthy R, Mohan K (2018) Review on effect machining parameters on performance of natural fibre–reinforced composites (NFRCs). J Thermoplast Compos Mater 32(9):1282–1302
2. Vinayagamoorthy R, Rajmohan T (2017) Machining and its challenges on bio-fibre reinforced plastics: A critical review. J Reinf Plast Compos 37(16):1037–1050
3. Mohan K, Rajmohan T. Fabrication and Characterization of MWCNT Filled Hybrid Natural Fiber Composites. Journal of Natural Fibers, 14(6):864–874.
4. Di Landro L, Lorenzi W, editors. (2009), Mechanical Properties and Dynamic Mechanical Analysis of Thermoplastic-Natural Fiber/Glass Reinforced Composites. Macromolecular symposia, Wiley Online Library.
5. Ashok R, Srinivasa C, Basavaraju BJAC, (2019), Dynamic mechanical properties of natural fiber composites—a review, 1–22.
6. Tang X (2020) Yan XJJoIT. A review on the damping properties of fiber reinforced polymer composites 49(6):693–721
7. Saba N, Jawaid M, Alothman OY et al (2016) A review on dynamic mechanical properties of natural fibre reinforced polymer composites 106:149–159
8. Salleh FM, Hassan A, Yahya R, et al, (2014), Effects of extrusion temperature on the rheological, dynamic mechanical and tensile properties of kenaf fiber/HDPE composites, 58:259–266.
9. Ornaghi HL Jr, Bolner AS, Fiorio R et al (2010) Mechanical and dynamic mechanical analysis of hybrid composites molded by resin transfer molding 118(2):887–896
10. Devi LU, Bhagawan S (2010) Thomas SJPc. Dynamic mechanical analysis of pineapple leaf/glass hybrid fiber reinforced polyester composites 31(6):956–965
11. Karaduman Y, Sayeed M, Onal L et al (2014) Viscoelastic properties of surface modified jute fiber/polypropylene nonwoven composites 67:111–118
12. Rajini N, Jappes JW, Rajakarunakaran S et al (2013) Dynamic mechanical analysis and free vibration behavior in chemical modifications of coconut sheath/nano-clay reinforced hybrid polyester composite 47(24):3105–3121
13. Shanmugam D, Thiruchitrambalam MJM (2013) Design. Static and dynamic mechanical properties of alkali treated unidirectional continuous Palmyra Palm Leaf Stalk Fiber/jute fiber reinforced hybrid polyester composites 50:533–542
14. Ramesh M, Palanikumar K, Reddy KHJR, et al, (2017), Plant fibre based bio-composites: Sustainable and renewable green materials,79:558–584.
15. Pappu A, Patil V, Jain S, et al, (2015), Advances in industrial prospective of cellulosic macromolecules enriched banana biofibre resources: A review,79:449–458.
16. Saba N, Paridah M, Jawaid MJC, et al, (2015), Mechanical properties of kenaf fibre reinforced polymer composite: A review,76:87–96.
17. Juárez C, Guevara B, Valdez P, et al (2010), Mechanical properties of natural fibers reinforced sustainable masonry,24(8):1536–1541.
18. Di Bella G, Fiore V, Galtieri G, et al. (2014),Effects of natural fibres reinforcement in lime plasters (kenaf and sisal vs. Polypropylene),58:159–165.
19. Ardanuy M, Claramunt J, Toledo Filho RDJC, et al. (2015), Cellulosic fiber reinforced cement-based composites: A review of recent research,79:115–128.
20. Joseph S, Sreekumar P, Kenny JM, et al, (2010), Dynamic mechanical analysis of oil palm microfibril-reinforced acrylonitrile butadiene rubber composites,31(2):236–244.
21. Mohanty S, Verma SK,Nayak SKJCS, et al (2006) Dynamic mechanical and thermal properties of MAPE treated jute/HDPE composites 66(3–4):538–547
22. Essabir H, Elkhaoulani A, Benmoussa K, et al (2013), Dynamic mechanical thermal behavior analysis of doum fibers reinforced polypropylene composites,51:780–788.
23. Mohanty H, Mahapatra MM, Kumar P et al (2012) Study on the effect of tool profiles on temperature distribution and material flow characteristics in friction stir welding. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226(9):1527–1535

24. Martínez-Hernández A, Velasco-Santos C, De-Icaza M, et al, (2007), Dynamical–mechanical and thermal analysis of polymeric composites reinforced with keratin biofibers from chicken feathers, 38(3):405–410.
25. Hammiche D, Boukerrou A, Djidjelli H, et al, (2018), Hydrothermal ageing of alfa fiber reinforced polyvinylchloride composites,47:293–300.
26. Di Landro L (2009) Lorenzi WJJoBM, Bioenergy. Static and dynamic properties of thermoplastic matrix/natural fiber composites 3(3):238–244
27. Scobbo Jr J, Nakajima NJPc (1991), Dynamic mechanical analysis of thermoplastic composites and resins,12(2):102–107.
28. Won JS, Lim SC, Park J, et al (2019), Microstructures and mechanical properties of thermoplastic composites based on polyarylate/nylon6 islands-in-sea fibers,40(S1):E484-E492.
29. Joseph P, Mathew G, Joseph K et al (2003) Dynamic mechanical properties of short sisal fibre reinforced polypropylene composites 34(3):275–290
30. Hristov V, Vasileva SJMM (2003), Engineering. Dynamic mechanical and thermal properties of modified poly (propylene) wood fiber composites,288(10):798–806.
31. Geethamma V, Kalaprasad G, Groeninckx G, et al (2005), Dynamic mechanical behavior of short coir fiber reinforced natural rubber composites,36(11):1499–1506.
32. Guo C-g, Song Y-m, Wang Q-w, et al (2006), Dynamic-mechanical analysis and SEM morphology of wood flour/polypropylene composites,17(4):315–318.
33. Brodowsky H, Mäder EJCS(2007), Technology. Jute fibre/polypropylene composites II. Thermal, hydrothermal and dynamic mechanical behaviour,67(13):2707–2714.
34. Tajvidi M, Motie N, Rassam G, et al (2010), Mechanical performance of hemp fiber polypropylene composites at different operating temperatures,29(5):664–674.
35. Arib R, Sapuan S, Ahmad M, et al (2006), Mechanical properties of pineapple leaf fibre reinforced polypropylene composites,27(5):391–396.
36. Joseph S, Appukuttan SP, Kenny JM, et al (2010) Dynamic mechanical properties of oil palm microfibril-reinforced natural rubber composites,117(3):1298–1308.
37. Shinoj S, Visvanathan R, Panigrahi S, et al (2011), Dynamic mechanical properties of oil palm fibre (OPF)-linear low density polyethylene (LLDPE) biocomposites and study of fibre–matrix interactions, 109(2):99–107.
38. Ghosh P, Bose NR, Mitra B, et al (1997), Dynamic mechanical analysis of FRP composites based on different fiber reinforcements and epoxy resin as the matrix material,64(12):2467–2472.
39. Jawaid M, Khalil HA, Bakar AA, et al (2013), Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites,47(13):1633–1641.
40. Jawaid M, Khalil HA, Hassan A, et al (2013), Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites,45(1):619–624.
41. Towo AN, Ansell MPJCS (2008), Technology, Fatigue evaluation and dynamic mechanical thermal analysis of sisal fibre–thermosetting resin composites,68(3–4):925–932.
42. Omar MF, Akil HM, Ahmad ZA, et al (2010), Dynamic properties of pultruded natural fibre reinforced composites using Split Hopkinson Pressure Bar technique,31(9):4209–4218.
43. Romanzini D, Lavoratti A, Ornaghi Jr HL, et al (2013), Influence of fiber content on the mechanical and dynamic mechanical properties of glass/ramie polymer composites,47:9–15.
44. Aziz SH, Ansell MPJCs (2004), The effect of alkalization and fibre alignment on the mechanical and thermal properties of kenaf and hemp bast fibre composites: Part 1–polyester resin matrix. 2004;64(9):1219–1230.
45. Rojo E, Alonso MV, Oliet M, et al (2015), Effect of fiber loading on the properties of treated cellulose fiber-reinforced phenolic composites,68:185–192.
46. Ray D, Sarkar B, Das S, et al (2002), Dynamic mechanical and thermal analysis of vinylester-resin-matrix composites reinforced with untreated and alkali-treated jute fibres. 2002;62(7–8):911–917.
47. Pickering KL, Efendy MA, Le, et al (2016) A review of recent developments in natural fibre composites and their mechanical performance. TMJCPAAS 83:98–112

48. Salman SDJDT (2020), Effects of jute fibre content on the mechanical and dynamic mechanical properties of the composites in structural applications. 2020;16(6):1098–1105.
49. Sezgin H, Berkalp O, Mishra R, et al (2016), Investigation of dynamic mechanical properties of jute/carbon reinforced composites,10(12):1492–1495.
50. Pothan LA, Potschke P, Habler R, et al (2005), The static and dynamic mechanical properties of banana and glass fiber woven fabric-reinforced polyester composite,39(11):1007–1025.
51. Saha A, Das S, Bhatta D, et al (1999), Study of jute fiber reinforced polyester composites by dynamic mechanical analysis,71(9):1505–1513.
52. Huda MS, Drzal LT, Mohanty AK, et al (2008), Effect of fiber surface-treatments on the properties of laminated biocomposites from poly (lactic acid)(PLA) and kenaf fibers,68(2):424–432.
53. Bogren KM, Gamstedt EK, Neagu RC, et al (2006), Dynamic–mechanical properties of wood–fiber reinforced polylactide: experimental characterization and micromechanical modeling,19(6):613–637.
54. Jawaid M, Alothman OY, Saba N, et al (2015), Effect of fibers treatment on dynamic mechanical and thermal properties of epoxy hybrid composites,36(9):1669–1674.
55. Sai NV, Kishore PN, Kumar, (2014) Investigation on dynamic behaviour of hybrid sisal/bagasse fiber reinforced epoxy composites. CPJIJoIRiAE 1(6):2349–2163
56. Sonia A, Dasan KP, Alex RJCej (2013), Celluloses microfibres (CMF) reinforced poly (ethylene-co-vinyl acetate)(EVA) composites: Dynamic mechanical, gamma and thermal ageing studies,228:1214–1222.
57. Sreenivasan V, Rajini N, Alavudeen A, et al (2015), Dynamic mechanical and thermo-gravimetric analysis of Sansevieria cylindrica/polyester composite: Effect of fiber length, fiber loading and chemical treatment,69:76–86.
58. Tao Y, Yan L, Jie RJToNMSoC (2006), Preparation and properties of short natural fiber reinforced poly (lactic acid) composites,19:s651-s655.
59. Ridzuan M, Majid MA, Afendi M, et al (2016), Thermal behaviour and dynamic mechanical analysis of Pennisetum purpureum/glass-reinforced epoxy hybrid composites,152:850–859.
60. Rajesh M, Pitchaimani JJJoRP (2017), Composites. Mechanical characterization of natural fiber intra-ply fabric polymer composites: Influence of chemical modifications,36(22):1651–1664.
61. Nair KM, Thomas S, Groeninckx GJCS, et al (2001), Thermal and dynamic mechanical analysis of polystyrene composites reinforced with short sisal fibres,61(16):2519–2529.
62. Vinayagamoorthy R, Rajeswari, (2014) Composites. Mechanical performance studies on Vetiveria zizanioides/Jute/glass fiber-reinforced hybrid polymeric composites, NJJoRP Technology 33(1):81–92
63. Rath J, Chaki T, Khastgir, (2012) Development of natural rubber-fibrous nano clay attapulgite composites: the effect of chemical treatment of filler on mechanical and dynamic mechanical properties of composites. DJPC technology 4:131–137
64. Finegan IC, Gibson, (2000) Analytical modeling of damping at micromechanical level in polymer composites reinforced with coated fibers. RFJCs, Technology 60(7):1077–1084
65. Herrera-Franco P, Valadez-Gonzalez, (2005) A study of the mechanical properties of short natural-fiber reinforced composites. AJCPBE 36(8):597–608
66. Hossain MK, Dewan MW, Hosur M, et al (2011), Mechanical performances of surface modified jute fiber reinforced biopol nanophased green composites,42(6):1701–1707.
67. Mazuki AAM, Akil HM, Safiee S, et al (2011), Degradation of dynamic mechanical properties of pultruded kenaf fiber reinforced composites after immersion in various solutions,42(1):71–76.
68. Mylsamy K, Rajendran, (2011) The mechanical properties, deformation and thermomechanical properties of alkali treated and untreated Agave continuous fibre reinforced epoxy composites. IJM, Design 32(5):3076–3084
69. Gardea F, Glaz B, Riddick J, et al. (2015), Energy dissipation due to interfacial slip in nanocomposites reinforced with aligned carbon nanotubes,7(18):9725–9735.
70. Wang Y, Zhan M, Li Y, et al. (2012), Mechanical and damping properties of glass fiber and mica-reinforced epoxy composites,51(8):840–844.

71. Han S, Chung (2012), Mechanical energy dissipation using carbon fiber polymer–matrix structural composites with filler incorporation, DJJoMS,47(5):2434–2453.
72. Rajini N, Jappes JW, Jeyaraj P et al (2013) Effect of montmorillonite nanoclay on temperature dependence mechanical properties of naturally woven coconut sheath/polyester composite 32(11):811–822
73. Ehlert GJ, Galan U,Sodano HAJAam, et al (2013) Role of surface chemistry in adhesion between ZnO nanowires and carbon fibers in hybrid composites 5(3):635–645
74. Tehrani M, Safdari M, Boroujeni A, et al. (2013), Hybrid carbon fiber/carbon nanotube composites for structural damping applications,24(15):155704.
75. Bansal D, Pillay S, Vaidya, (2013) Nanographite-reinforced carbon/carbon composites. UJC 55:233–244
76. Chandradass J, Kumar MR, Velmurugan, (2007) Effect of nanoclay addition on vibration properties of glass fibre reinforced vinyl ester composites. RJML 61(22):4385–4388
77. Iqbal A, Frormann L, Saleem A, et al. (2007), The effect of filler concentration on the electrical, thermal, and mechanical properties of carbon particle and carbon fiber-reinforced poly (styrene-co-acrylonitrile) composites,28(2):186–197.
78. Zhang R-x,Ni Q-Q, Natsuki T, et al (2007) Mechanical properties of composites filled with SMA particles and short fibers 79(1):90–96
79. Praveen S, Chakraborty B, Jayendran S, et al (2009), Effect of filler geometry on viscoelastic damping of graphite/aramid and carbon short fiber-filled SBR composites: A new insight,111(1):264–272.
80. Khan SU, Li CY, Siddiqui NA, et al. (2011), Vibration damping characteristics of carbon fiber-reinforced composites containing multi-walled carbon nanotubes,71(12):1486–1494.
81. Ferreira J, Capela C (2011) Costa JJS (2011). Dynamic mechanical analysis of hybrid fibre/glass microspheres composites. 47(3):275–280
82. Icduygu MG, Aktas L, Altan. (2012) Characterization of composite tiles fabricated from poly (ethylene terephthalate) and micromarble particles reinforced by glass fiber mats. MCJPc 33(11):1921–1932
83. Uthayakumar M, Manikandan V, Rajini N, et al. (2014), Influence of redmud on the mechanical, damping and chemical resistance properties of banana/polyester hybrid composites,64:270–279.
84. Wang T, Zhang J,Zhang YJJoRP, et al (2014) Forming process and damping properties of carbon fiber-reinforced polymer concrete 33(1):93–100
85. Satapathy S, Kothapalli (2015), Influence of fly ash cenospheres on performance of coir fiber-reinforced recycled high-density polyethylene biocomposites, RVJJoAPS,132(28).
86. Huang C, Huang Z, Qin Y, et al (2016), Mechanical and dynamic mechanical properties of epoxy syntactic foams reinforced by short carbon fiber,37(7):1960–1970.

Investigation on Wear Performance of Sisal Fiber Reinforced Epoxy Composites: Experimental and Statistical Study

K. Palani Kumar, A. Shadrach Jeya Sekaran, and K. Ramya

Abstract Sisal natural fiber is an alternative used in engineering applications for manufacturing a variety of products. The present study focuses on the wear performance of woven sisal fiber- epoxy composites using a mathematical model. The experiments were conducted on a pin-on-disc wear tester against EN8 steel by adopting the design of experiments (DOE). Wear loss is predicted by the second-order polynomial Response Surface Method (RSM), and its predictability is asserted by considering the analysis of variance (ANOVA). The parameters applied load, sliding speed, and sliding distance are also investigated in detail. Model suitability is analyzed. From the analysis, it is evident that the model is useful to evaluate the wear performance of sisal fiber epoxy composites.

Keywords Sisal · Natural fiber · Wear loss · Coefficient of friction · Pin on disc · Design of experiment (DOE) · Response surface method (RSM)

1 Introduction

The green environment for the future has been initiated by the researchers with increased interest to go for alternative materials using synthetic fibers. The abundant availability of nature leads to the usage of natural fibers. They have low density with good specific strength, non-hazardous and eco-friendly [1–18]. Building the global environment with the individual attention towards the society and framing the novel

K. Palani Kumar (✉)
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, West Tambaram, Chennai, India

A. Shadrach Jeya Sekaran
Department of Mechanical Engineering, St. Peter's College of Engineering and Technology, Chennai 600054, India

K. Ramya
Department of Civil Engineering, Sri Sai Ram Institute of Technology, West Tambaram, Chennai, India
e-mail: ramya.civil@sairamit.edu.in

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_18

environmental policies have enforced the search for green composite materials said to be natural fiber composites [2–4]. Agricultural wastes obtained from rice, sugar cane, pineapple, banana, and coconut are being used for producing a huge quantity of biomass. Natural fibers are also used in various industries as an alternative to the raw materials for manufacturing automotive components. The following literature gives an idea of the multiple goods in manufacturing industries [3–20].

Palanikumar et al. [14] have studied the analysis of different woven composites and found that these composites are suitable for automobiles and related applications . The loss of mass on the surface of a solid progressively is said to be wear [12]. Natural fibers are utilized in various applications of wear and friction. Abrasive wear rates were tested for the bagasse fiber- epoxy and found that the fiber orientation also influences the wear rate [16]. Alkali and acid-treated rice straws are considered to remove impurities, waxy substances and it also improves the quality of fiber. From the observation, enhancement of mechanical properties is identified [17]. Tribological properties of PALF short fiber polymer have experimented for different lengths of range from 2 to 14 mm. load escalates the wear at various loads of like 5 N, 10 N, and 15 N [21].

The hand lay-up process in which the fabrication of sisal fiber polymer is done by adopting a particular weight fraction concerning length variation. They have asserted that the variables considered are directly related to responses [19]. An increase in the ratio of glass fiber weight fraction and parallel sliding direction decreases the coefficient of friction and also increases the rate of wear [11]. The wear rate decreases for the increase of fiber weight in percentage [14].

Short palmyra fiber composites are tested for dry sliding, and found that the fiber percentile and sliding speed are the unique elements that affect the wear. Specific wear rate is predicted beyond the experimental domain[20] polyester composite along with particulate reinforcements are considered to analyze the wear by using Pin on disc tribometer for various speeds as well as loads, the wear resistance is higher for fiber-loaded composite [12]. Natural fiber has comparable mechanical properties and also has an improved resistance to wear. The orientation normal to the sliding is found to be the best orientation, it is considered to be the main parameter that affects the wear and friction [16]. The sisal fibers have excellent resistance to wear hence used for the manufacture of fiberboard, its suitability is to be studied further [15]. The study on natural fibers reveals that, enhancement in wear is obtained for 36% hybrid natural fiber when compared to 12 and 24%. This study suggests that this can be used for replacing the bones or orthopedic implant in humans [22]. Sisal/jute—epoxy is fabricated and tested for wear and its frictional properties with different loads, speeds, and distance inferred that the alkali treatment reduces the wear [10]. The features of sisal-vinyl ester composites are modeled and presented by using Box-Behnken Design with better optimization [2].

From the analysis, it is found that only very little literature is available, and minimal work is undertaken for referring to the wear properties of woven sisal epoxy composite. No comprehensive experimental design or analysis for woven sisal composites is carried out using Box-Behnken Design. The woven sisal fiber replaces traditional fibers and also has good improvement in the properties of friction and wear applications. Based on the research gap identified, woven-sisal fiber composite is prepared, its tribological characteristics are analyzed and tested. Modeling and optimization are carried out for wear experiments by statistical analysis with the design of experiments using the Box-Behnken model.

2 Materials and Methods

In the present day, natural fibers are considered essential reinforcing agents due to their eco-friendly nature. Also, the cost of manufacturing is found to be low. It has other characteristics like high specific strength, non-abrasiveness, etc. Sisal natural fiber is considered for the present investigation. Figure 1a–c shows the sisal plants, the extraction of sisal fiber, and the woven sisal fiber mat. Epoxy resin is used for the fabrication of composites as a matrix and has better properties than other resin like stiffness, strength, etc. [6]. The hand lay-up process is considered for fabricating the composites. The sisal composite laminates are cut into pre-wear specimens of size 60 × 12 × 12 mm, which is illustrated in Fig. 1d. The prepared samples are turned into cylindrical pins by using all geared lathe which are represented in Fig. 1e. Pin-wear specimens of the circular shapes are made as per ASTM standard G99 having a length of 50 mm and diameter of 8 mm and are shown in Fig. 1f.

In this investigation, the wear property is analyzed using a tribometer. In this experimental study, the woven sisal fiber composite tribological characteristics are experimented with by various parameters: load, speed, and sliding distance. The

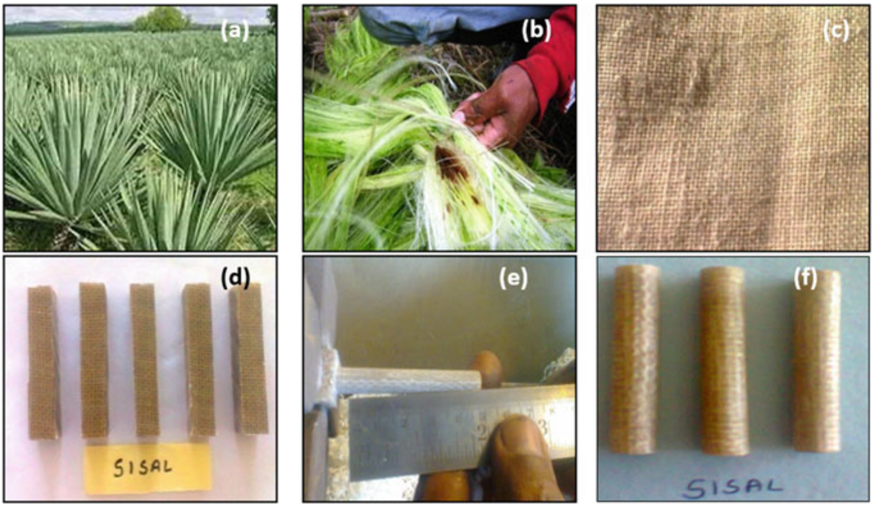


Fig. 1 **a** Sisal plants **b** Extraction of sisal fiber **c** Woven Sisal fiber **d** Sisal Specimens **e** Machining of sisal specimen **f** Wear Specimens

Fig. 2 Pin on disc tribometer experimental set up

Table 1 Parameters and levels considered for experiments

Parameters	Levels		
	− 1	0	1
Applied load (N)	9.81	19.62	29.43
Sliding speed (m/s)	1.44	2.16	2.88
Sliding distance (m)	1000	2000	3000

disc is prepared for the testing process, having a 55 mm diameter and thickness of 10 mm. A hole is drilled in the middle for fixing purposes. The disc material is EN8 steel. The pin is set in the holder perpendicular to the disc for abrasion. For different speeds, distances and times, the wear rate is observed and recorded. The pin-on-disc machine setup is presented in Fig. 2. The tribological parameters used and their levels identified are given in Table 1.

3 Modeling the Tribological Parameters Using Box-Behnken Design

Research is sorted out in the arrangement of exercises to consider, build a model or procedure. It finds the consequences of a sensible issue upheld by writing and testing information. With the end goal that its destinations are streamlined and further make suggestions for implementations. In this investigation, response surface methodology (RSM) is considered for studying the tribological properties using Box-Behnken design. In RSM problems, the connection between the reaction and the free factors is not known. Accordingly, the initial phase in RSM is to locate an appropriate estimation for the genuine utilitarian connection among ‘y’ and set of free factors. On the off chance that the reaction is very much demonstrated by a straight work in the autonomous factors, at that point the approximating capacity in the principal request model is composed as:

(1) If the curvature is considered:
(2) A second-order quadratic equation is considered for analysis by considering the variables such as applied load (W), sliding speed (N), and sliding distance (S). Experiments are carried out using Box-Behnken design. The selected factors are coded as −1, 0, + 1, and it is arranged in equally spaced values. It has a square term of products of two factors, to arrive in a quadratic model. The ratio of experimental points to the number of coefficients is within the range of 1.5–2.6. Depending on the distance from the center, the estimated variance approximately lies at a higher level inside, the smallest cube containing the experimental points.

Figure 3a, b and Table 2 show Box-Behnken design consisting of three factors. The wear loss is found by using pin- on- disc tribometer by varying the parameters W, N, and S. The weight loss for each sample is experimentally obtained by varying loads are 9.81, 19.62, and 29.43 N. The test is carried out as per the Box Behnken design of experiments and the details are illustrated in Table 3.

The quadratic model established for the wear loss of sisal fiber-reinforced composite is presented as follows:

$$\begin{aligned}
&\text{Wear loss} = +0.56563 + (7.67074\text{E} - 003 * W) \\
&- (0.24097 * N) - (2.74000\text{E} - 004 * S) + (3.22092\text{E} - 003 * W * N) \\
&+ (7.41590\text{E} - 006 * W * S) + (5.90278\text{E} - 006 * N * S) \\
&- \left(4.01357\text{E} - 004 * W^2\right) + \left(0.052807 * N^2\right) + \left(6.08750\text{E} - 008 * S^2\right)
\end{aligned}$$

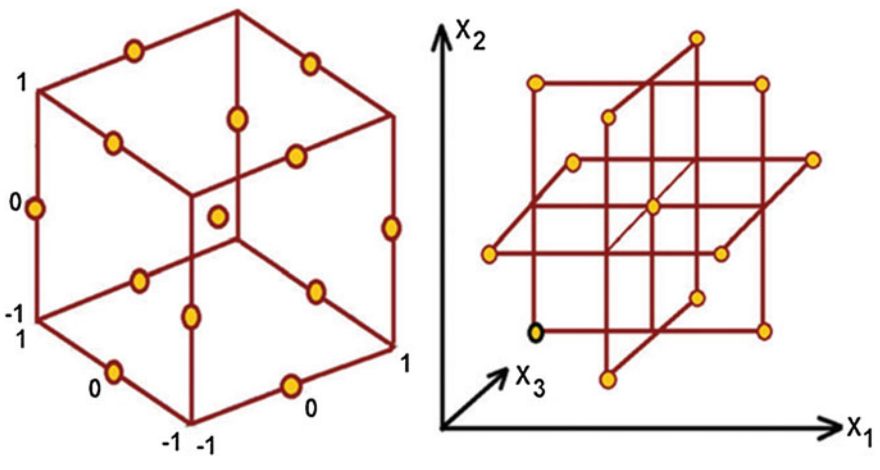


Fig. 3 Box-Behnken design matrix for three factors: **a** A cubical design and **a** Interlocking 2^2 factorial design

Table 2 Three variable Box-Behnken design

Run	x_1	x_2	x_3
1	−1	−1	0
2	1	−1	0
3	−1	1	0
4	1	1	0
5	−1	0	−1
6	1	0	−1
7	−1	0	1
8	1	0	1
9	0	−1	−1
10	0	1	−1
11	0	−1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0

where W is applied load, N is sliding speed, and S is the sliding distance.

The results of ANOVA obtained for sisal fiber-reinforced composite material are presented in Table 4, which proves that the applied load is the primary factor, which impacts the wear loss followed by sliding distance. The model adequacy is checked by utilizing the coefficient of correlation. The ratio of correlation observed for wear loss for sisal fiber-reinforced composite is 0.9965, which shows that the models developed are beneficial. F- Model value 218.89 shows that the model is noteworthy. In this case, W, N, S, WN, WS, W^2, N^2, S^2 are capable. The "Lack of Fit F-value" of 3.34 infers which isn't huge concerning the unadulterated mistake, and hence the model is in fit. The model statistics for the wear loss of sisal fiber reinforced plastic composite are also presented in Table 4. The model statistics indicate that the standard deviation is 0.013, and the coefficient of correlation R-Sq is 0.9965, which suggests that the model is valid.

The adjacent R-Sq is observed as 0.9919, and the predicted R-Sq is 0.9579. The predicted R-Sq of 0.9579 is in good correlation with the observed R-Sq of 0.9919. Adequate precision of 52.183 infers that the model has an appropriate signal. This indicates that the model is very useful in predicting wear loss for sisal fiber-reinforced polymer composite. Further, the effectiveness is analyzed by the normal plot of residuals and the correlation graph, which are presented in Fig. 4a, b.

The normal probability of the plot indicates that there is a normality assumption. The points in the model are said to be grouped in a straight line, which suggests that the model is beneficial. Figure 5 indicates the residual analysis of the wear loss model.

Table 3 Box-Bhenken Experimental design used and results obtained for wear loss and co efficient of friction for Sisal fiber reinforced composite

Std order	Run order	Parameters						Responses	
		Coded values			Real values			Wear loss mm^3/m	Coefficient of friction
		Applied Load (x_1) N	Sliding speed (x_2) m/s	Sliding Distance (x_3) m	Applied Load (W) N	Sliding speed (N) m/s	Sliding Distance (S) m		
1	3	−1	−1	0	9.81	1.44	2000	0.256	0.449
2	5	1	−1	0	29.43	1.44	2000	0.486	0.528
3	6	−1	1	0	9.81	2.88	2000	0.318	0.497
4	15	1	1	0	29.43	2.88	2000	0.639	0.64
5	7	−1	0	−1	9.81	2.16	1000	0.276	0.485
6	4	1	0	−1	29.43	2.16	1000	0.393	0.732
7	14	−1	0	1	9.81	2.16	3000	0.378	0.528
8	17	1	0	1	29.43	2.16	3000	0.786	0.513
9	11	0	−1	−1	19.62	1.44	1000	0.361	0.497
10	1	0	1	−1	19.62	2.88	1000	0.424	0.733
11	2	0	−1	1	19.62	1.44	3000	0.616	0.562
12	12	0	1	1	19.62	2.88	3000	0.696	0.512
13	9	0	0	0	19.62	2.16	2000	0.449	0.589
14	10	0	0	0	19.62	2.16	2000	0.437	0.581
15	13	0	0	0	19.62	2.16	2000	0.423	0.593
16	16	0	0	0	19.62	2.16	2000	0.434	0.584
17	8	0	0	0	19.62	2.16	2000	0.437	0.596

Table 4 Analysis of variance for wear loss of sisal fiber reinforced composite

Source	Sum of squares	df	Mean square	F value
Model	0.34	9	0.038	218.89
W- Applied Load	0.14	1	0.14	841.06
N-Sliding speed	0.016	1	0.016	93.1
0.13	1	0.13	758.76	< 0.0001
WN	2.07E-03	1	2.07E-03	12.03
WS	0.021	1	0.021	123.03
NS	7.23E-05	1	7.23E-05	0.42
W^2	6.28E-03	1	6.28E-03	36.51
N^2	3.16E-03	1	3.16E-03	18.34
S^2	0.016	1	0.016	90.68
Residual	1.21E-03	7	1.72E-04	
Lack of Fit	8.61E-04	3	2.87E-04	3.34
Pure Error	3.44E-04	4	8.60E-05	Pred

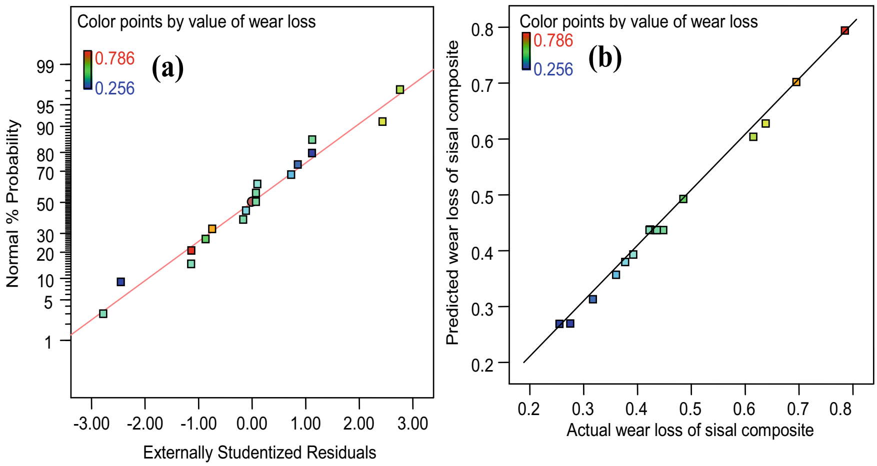


Fig. 4 Normal probability and Correlation graph on wear loss

Figure 5a provides the residuals and the predicted wear loss. The results indicate both positive and negative residuals, which show that the residuals are spread in both directions. This explains the uniform predictability of the model. Figure 5b indicates the relation between the residuals and run numbers. The variations observed in the residuals are low, which shows the effectiveness of the model.

The coefficient of friction (COF) for sisal fiber-reinforced composite is calculated from a pin on disc tribometer by varying W, N, and S. The wear test is carried out

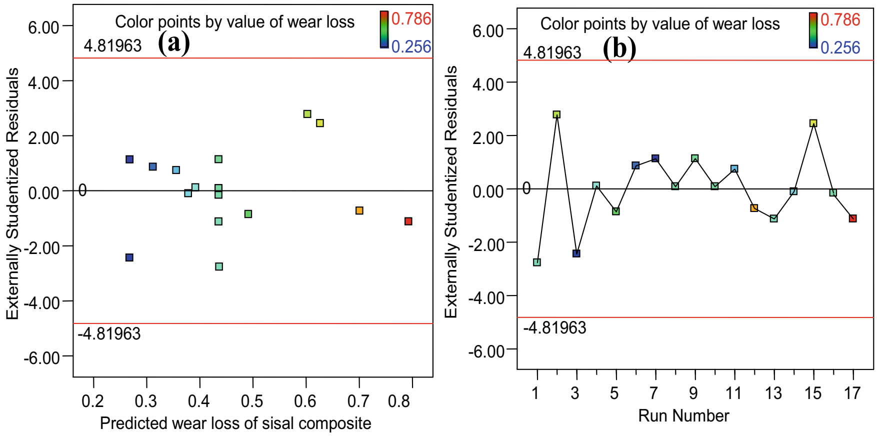


Fig. 5 Residual analysis for wear loss for Sisal fiber reinforced composite

as per the Box Behnken design of experiments in statistics. The parameters and various levels considered are provided in Table 3. The ANOVA prediction obtained for COF is presented in Table 5. From the design values, mathematical relations are established. The quadratic model established is presented as follows:

$$\begin{aligned} &\text{Coefficientoffriction} = -0.48175 + (0.028843 * W) \\ &+(0.41674 * N) + (2.57200\text{E} - 004 * S) + (2.26526\text{E} - 003\text{W} * N) \\ &-(6.67686\text{E} - 006 * W * S) - (9.93056\text{E} - 005 * N * S) \\ &-\left(3.72002\text{E} - 004 * \text{W}^2\right) - \left(0.04687 * \text{N}^2\right) + \left(1.17000\text{E} - 008 * S^2\right) \end{aligned} \quad z \qquad (2)$$

where W is applied load, N is sliding speed, and S is the sliding distance.

ANOVA performed for COF is presented in Table 5. The result proves that the applied load is an effective factor, which influences the wear loss followed by sliding speed. R-Sq value is used to know the model capability and is 99.71, which shows the model's effectiveness. The F-model value 263.56 shows that the model is noteworthy. In this investigation, W, N, S, WN, WS, NS, W^2, N^2, S^2 are effective. The "Lack of Fit F-value" of 1.28 infers which isn't huge concerning the unadulterated mistake, and the model is said to be fit. The model statistics for the COF are presented in Table 5. The model statistics indicate that the coefficient of correlation R- sq is 0.9971, which suggests that the model is adequate.

The adjacent R-Sq is observed as 0.9933, and the predicted R-Sq is 0.9746. The difference is less than 0.2. The result indicates that pred- R-Sq 0.9746 has a good correlation towards the adjacent R-Sq 0.9933, which suggests the model is beneficial. The adequate precision 57.291 demonstrates that the model helps in predicting the coefficient of friction for sisal fiber-reinforced polymer composite. Further, the effectiveness of the model is analyzed by considering the probability plot of residuals, and the correlation graph, which is presented in Fig. 6a, b. The normal probability

Table 5 Analysis of variance for coefficient of friction of sisal fiber reinforced composite

Source	Sum of squares	df	Mean square	F Value	p-value	Prob > F
Model	0.1	9	0.011	263.56	<	Significant
W-Applied Load	0.026	1	0.026	600.77	<	
N-Sliding speed	0.015	1	0.015	348.94	<	
S-Sliding Distance	0.014	1	0.014	321.27	<	
WN	1.02E-03	1	1.02E-03	23.88	<0.00	
WS	0.017	1	0.017	400.16	<	
NS	0.02	1	0.02	476.83	<	
W^2	5.40E-03	1	5.40E-03	125.83	<	
N^2	2.49E-03	1	2.49E-03	57.97	<0.00	
S^2	5.76E-04	1	5.76E-04	13.44	<0.00	
Residual	3.00E-04	7	4.29E-05			
Lack of Fit	1.47E-04	3	4.90E-05	1.28	0.39	Not significant
Pure Error	1.53E-04	4	3.83E-05			
Cor Total	0.1	16				
R-squared	0.9971	Adj	R-squared		Pred R-squared	0.9

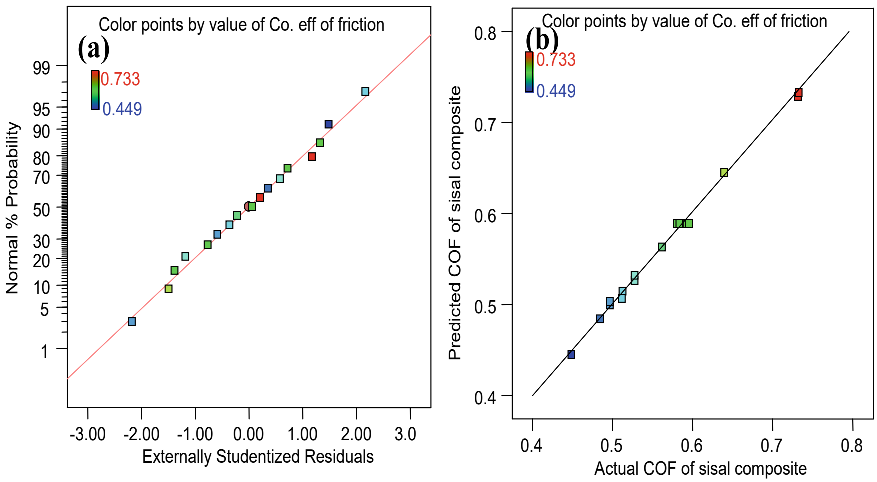


Fig. 6 Normal probability and Correlation graph on co efficient of friction

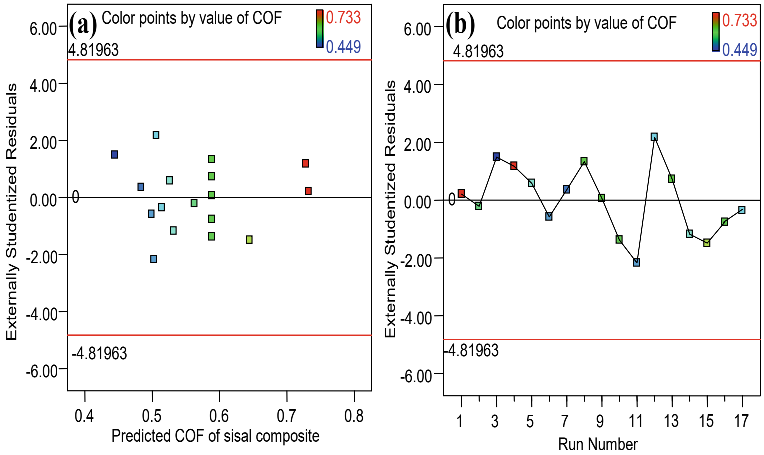


Fig. 7 Residual analysis for co efficient of friction

plot shown proves that there is a normality assumption. The points in the model are said to be grouped in a straight line, which leads to the model being very effective. Figure 7 indicates the residual analysis of the coefficient of the friction model.Fig. 7a provides the residuals and the predicted coefficient of friction. The results indicate both positive and negative residuals, which show that the residuals are spread in both directions. This explains the uniform predictability of the model. Figure 7b provides the relation between the residuals and run numbers and it gives the changes in residuals concerning the run number, and it shows that the model considered is stable. The comparative wear results of sisal fiber composite experiment runs are presented in Fig. 8. The values show the coefficient of correlation between the model developed for tribological testing of sisal composite. The results indicate that the models are fit. The comparison results indicate that the developed model *R-Sq* values are better and closer; hence, this model can be adequately utilized for the forecast of various reactions. The confirmation experiment is carried out for the experiment run of 2, 8, and 12 for wear loss. The comparative test result for the above-said experiment runs along with the experiment, and the predicted and confirmation values are presented in Fig. 9.

The confirmation experiments are carried out for the experiment run of 1, 6, and 14 for sisal fiber-reinforced composite for the coefficient of friction (COF) related to different parameters. From the verification test results, the experimental results and anticipated results are well correlated with each other, and also the error obtained is small. Hence, the model is effective in predicting the tribological characteristics.

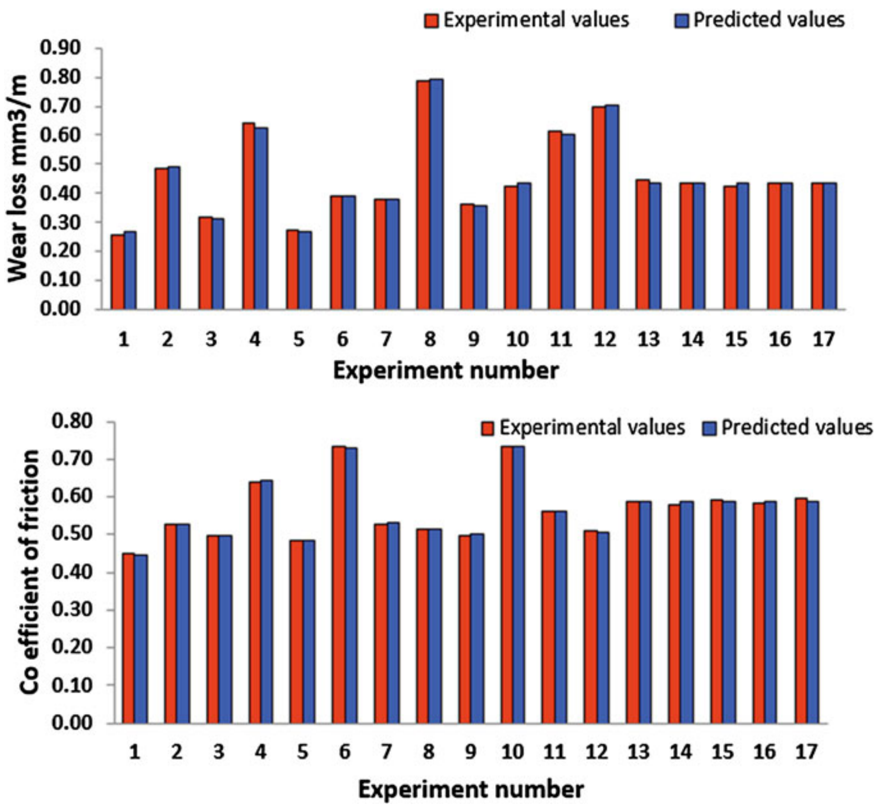


Fig. 8 Comparison chart between the experimental results and RSM predicted results for wear loss and coefficient of friction for Sisal fiber composite

4 Results and Discussions

Nowadays, researchers are making progress in replacing synthetic fibers with natural fibers. natural fibers have made their advancements in different areas of Engineering and Technology. Because of its biodegradability, it supports the environment and is also cost-effective. The tribological properties are evaluated for the wear loss and COF for sisal fiber composite by using the Design of Experiment (DOE). Scanning Electron Microscope (SEM) images are considered to dissect the surface.

The wear loss and COF are experimented with and predicted by a pin-on-disc tribometer and by response surface methodology. It is calculated by varying the parameters such as applied loads with different speeds of sliding of 1.44, 2.16, and 2.88 m/s and its variation of sliding distances of 1000, 2000, and 3000 m, respectively. The cylindrical pins prepared from the sisal fiber-reinforced composite samples are made to contact a rotating disc on testing; thus, weight loss for each sample is experimentally obtained by varying the input parameters load, speed, and distance.

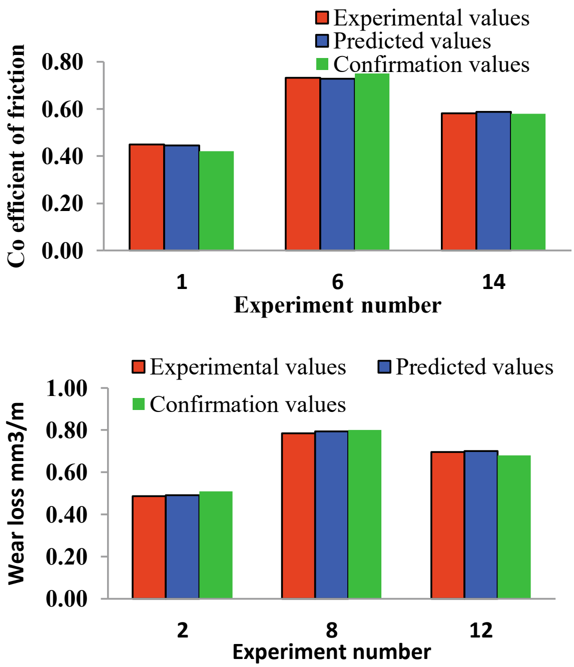


Fig. 9 Verification test result between the experimental, RSM predicted and confirmation experiment results for wear loss and coefficient of friction for Sisal fiber composite

The sample graphs generated from the data acquisition system of the pin-on-disc testing apparatus for sisal fiber-reinforced composite pins, tested under loads of 9.81 to 29.43 N, and the distance of 1000 - 3000 m is represented in Fig. 10. The graph is plotted among the time, applied load, and coefficient of friction. In the graph, it is inferred that there is wear due to the toughness of the fibers.

Sisal fiber-based pins are subjected to similar experimental conditions, which are discussed above, and the parameters concerning wear loss are calculated. When the sliding speed is at 2.16 m/s, the pin is allowed to travel at 2000 m distance for various load conditions, the wear loss is found to increase at a higher rate. The obtained output graph from the model developed is presented in Fig. 11a. When 19.62 N of the load is applied for the same sisal fiber-reinforced composite pin for a 2000 m distance and the sliding speed is varied and there is not much effect in the wear loss, it is shown in Fig. 11b. Then, for a similar load and the speed of sliding 2.16 m/s with a different distance, the wear loss is found to be increased, and it is presented in Fig. 11c.

When the interaction between the parameters is considered for wear loss for sisal fiber-reinforced composite, the sliding speed increases from minimum to maximum concerning load and increases the wear rate. When the distance of sliding is increased from lower to a higher one concerning the increase in load, the wear rate is found to be increased only at maximum distance. Similarly, the distance increases from low to high concerning speed; the wear loss shows only little effect. From the interaction graphs, the trend of applied load concerning sliding distance and sliding speed shows

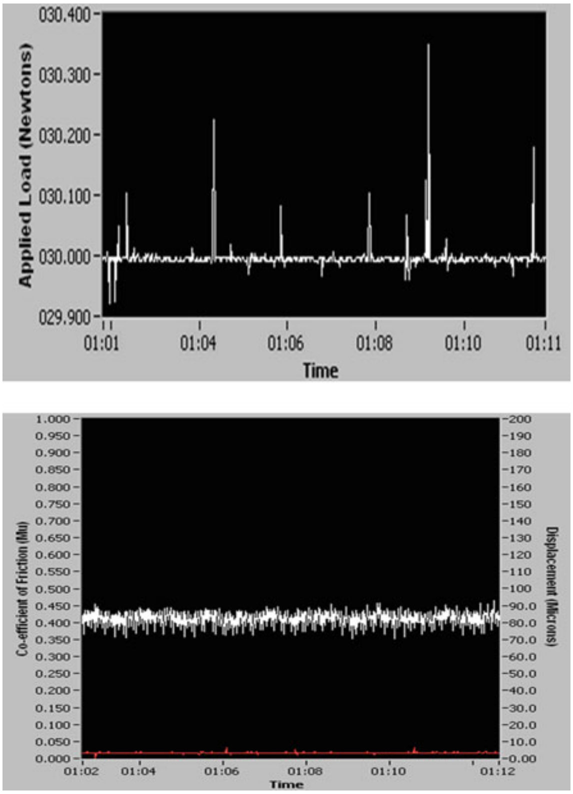


Fig. 10 Typical wear track image of applied load and co-efficient of friction with time for Sisal fiber reinforced composite specimen

useful variations for the difference in minimum and maximum values of all the factors considered.

Similarly, the other response, COF concerning load, speed, and distance for sisal fiber-reinforced composite is obtained. When the rate is at 2.16 m/s and the sisal pin is made to travel at a 2000 m for various load conditions, the COF is increasing at a higher rate, shown in Fig. 12a. When 19.62 N of the load is applied for the same sisal fiber-reinforced composite pin for a sliding distance of 2000 m and the sliding speed is varied there is not much effect in the coefficient of friction, it is shown in Fig. 12b. Then, for the same load of 19.62 N and 2.16 m/s with the difference in sliding distance, the coefficient of friction is observed to be minimum, and it is presented in Fig. 12c. Here, the high volume of the coefficient of friction is noted for load, then for speed, and finally, it tends to reduce concerning distance.

When the interaction between the parameters is considered for the coefficient of friction for sisal fiber-reinforced composite, that when the sliding speed increases and the coefficient of friction is found to be minimum, and it decreases for maximum speed concerning the changes of load. Then, when the sliding distance is increased from lower to a higher one for a constant sliding speed concerning variations of load, the COF is found to be higher for minimum distance and lower for maximum length

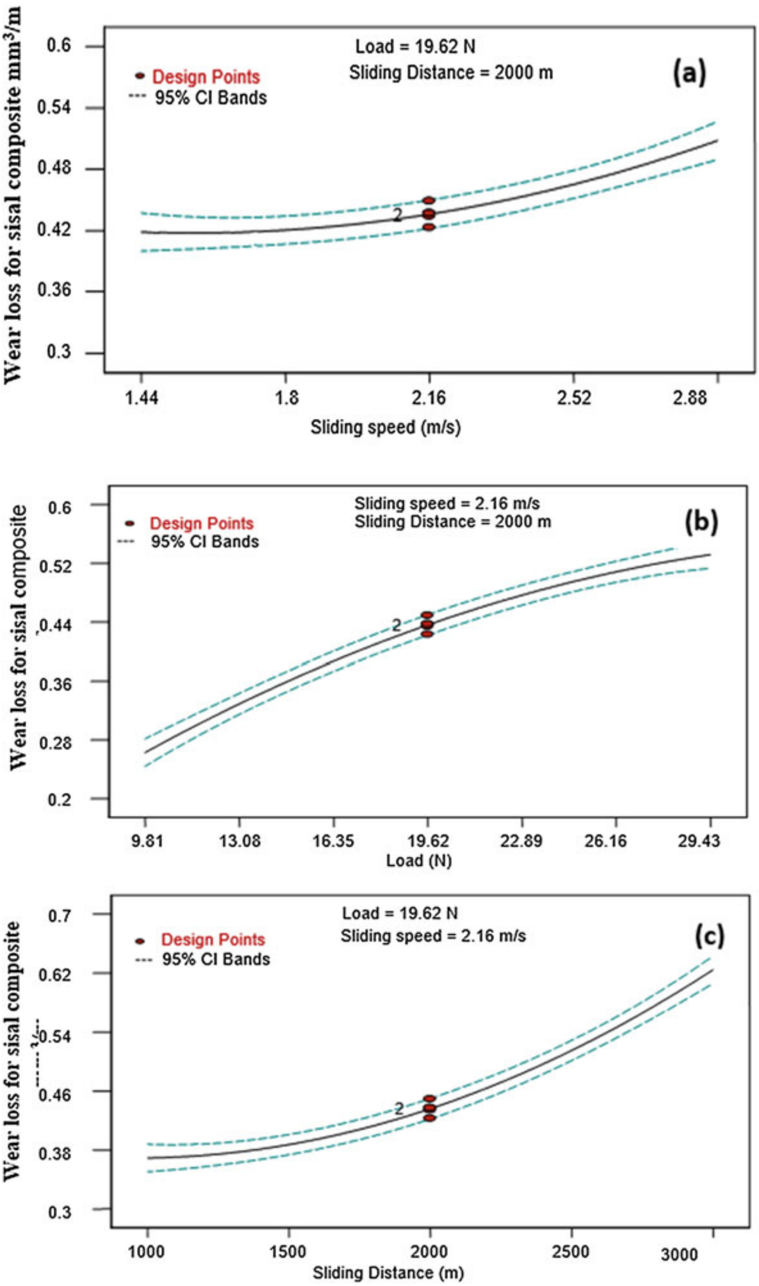


Fig. 11 Effect of wear loss for sisal fiber reinforced composites with respect to different parameters

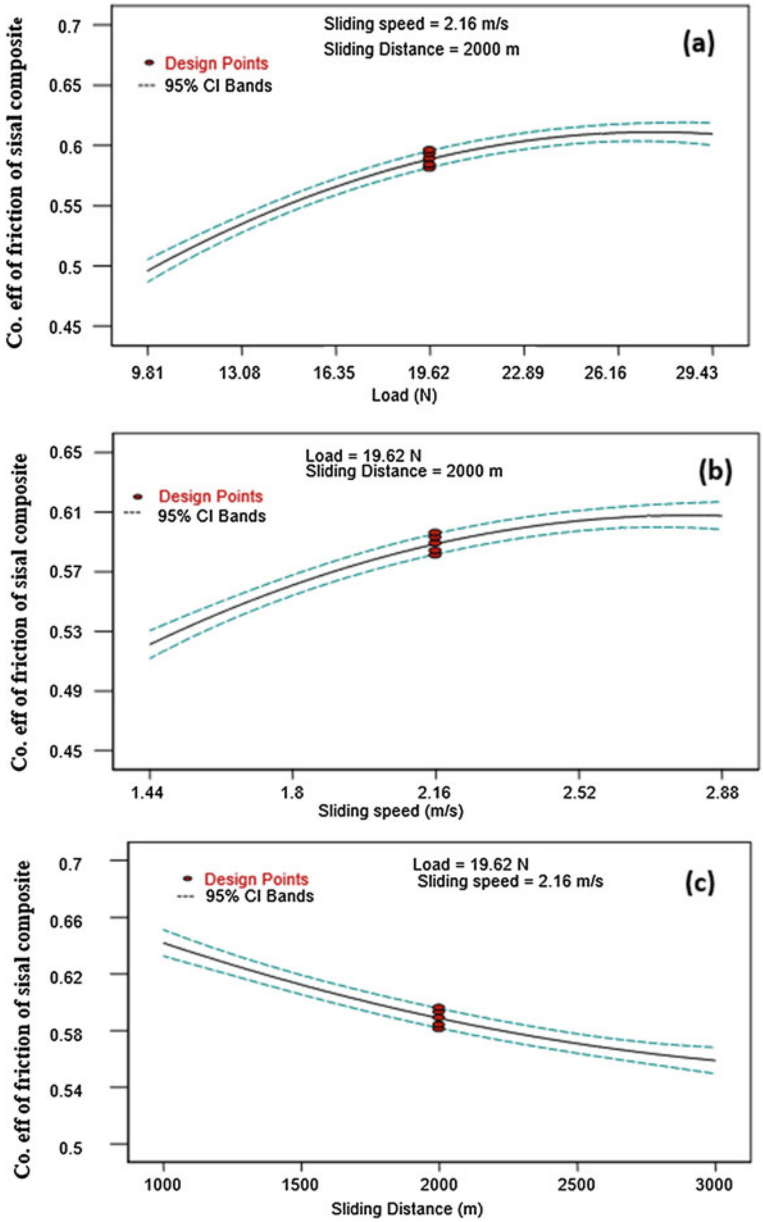


Fig. 12 Effect of Coefficientof friction of sisal fiber reinforced composites with respect to different parameters

traveled. Similarly, when the distance is increased concerning speed, the coefficient of friction shows high variation. It is observed, from the initial stage, that there is a good variation in the coefficient of friction of sisal fiber-reinforced composite when the load is varied for different speeds concerning distance travel of 2000 m. It is observed that, when the load increases, the coefficient of friction increases.

The distance is varied concerning different loads for the minimum distance and the coefficient of friction is found to be increased. For maximum distance, the coefficient of friction is found to be decreased. Similarly, for various sliding speeds concerning different sliding distances and considering the applied load as constant and is 19.62 N, the COF observed is maximum for minimum distance and maximum for maximum distance.

The 3D response graph is also generated for the variation of parameters, W, N, and S regarding wear loss and COF for the sisal composite pin specimen. Here, in the 3D graph, a clear view of the wear loss is seen. It is found to increase by the variation of load, and it is presented in Fig. 13a. When the load is increased the concerning distance and the wear loss is maximum, and it is observed in the mesh by a change in red color, and it is presented in Fig. 13b. Wear loss is found to be minimum for change in sliding speed and increases concerning distance, and is indicated in Fig. 13c. Similarly, the 3D response bgraph is also generated for COF regarding the applied load, sliding distance, and sliding speed. It shows a precise observation that the coefficient of friction decreases when sliding speed and load are made to increase. It is maximum when load and distance have increased, and it is represented in Figs. 13d–f.

Sisal fiber composite is observed to have minimum wear resistance property. This is due to the toughness of the fiber. So, it can be suggested to be utilized in moderate applications such as clutch pads, brake pads, and leaf springs. Wear mechanisms in polymer composites are said to be adhesive, abrasive, and fatigue wear. On a smooth surface, usually, adhesive wear occurs. In hard or rough surfaces, abrasive and fatigue wear will appear [20]. The mechanisms observed mostly are the delamination of fiber and micro plowing. The wear loss gets increased by scaling of distance, due to the consistent material removal. The orientation of fiber makes the difference in wear mechanism, and the recommended one is a normal orientation towards rubbing direction. Based on the natural fiber matrix selected, the wear and friction get varied based on the volume fraction of fibers and applied load. Typically, the wear increased concerning the increase of fiber content.

Sisal fiber-reinforced composite specimen after wear testing indicates that there is an increase in depth of penetration on the matrix in the wear track. As well, the fibers also get protruded out on the wear track from the different magnification factors of images. This observation indicates that wear takes place not only for the matrix but also for fiber. Micro pits are developed on the worn area because of the adhesive action of pins and composites applied load [21–23].

Due to adhesion, the matrix fiber detaches from the surface which results in wear track on the composite. In some locales, fragile epoxy resin has been confined because of high weight and plastic distortion, and after that, flotsam and jetsam are made. It

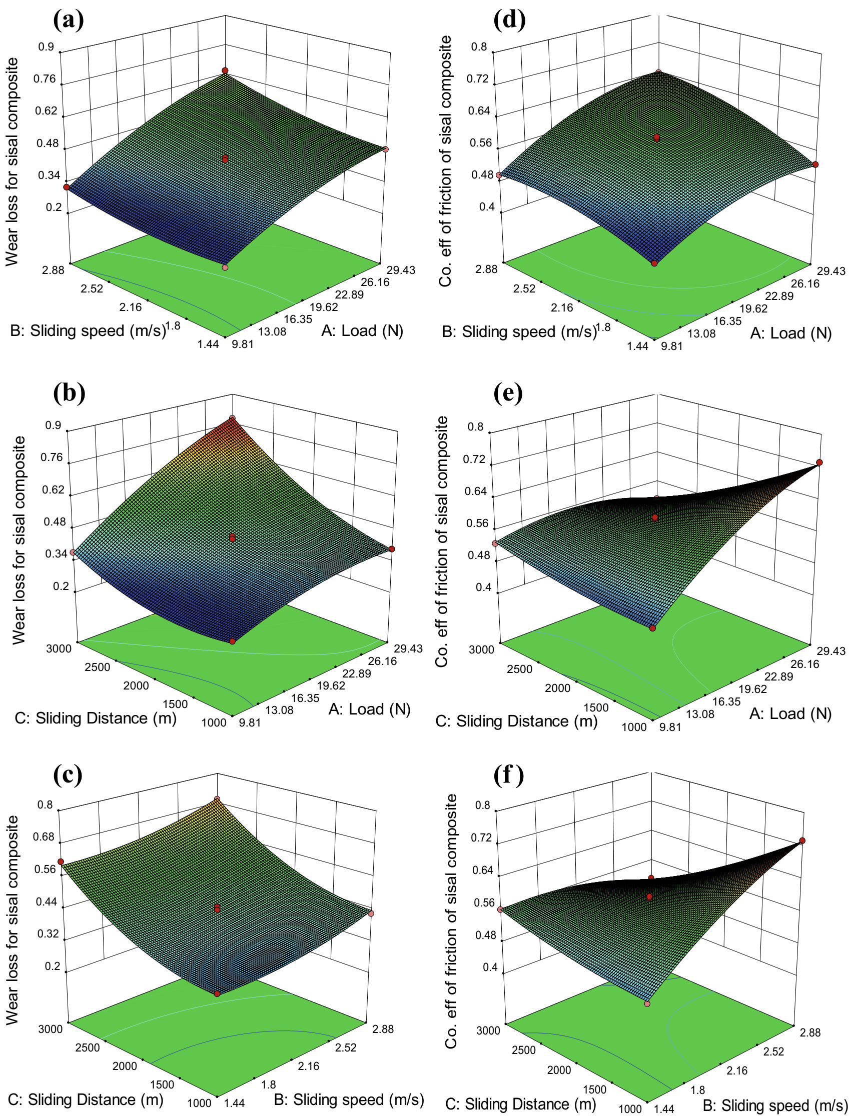


Fig. 13 Three D response graph for wear loss and Coefficientof friction for sisal fiber reinforced composites

is inferred from the results that natural strands are viable to improve the tribological properties.

5 Conclusions

- The investigation aims to find a replacement for synthetic fibers in composites. There has been limited study on woven sisal reinforcements. In this investigation, the tribological behavior of sisal composites is carried out.
- Modeling is carried out for wear experiments by statistical analysis using Box-Behnken design.
- The analysis of the results is carried out for the tested specimen using SEM,
- Studies on natural fiber have drastically increased because of its essential properties and environmental adaptability. Wear is determined for sisal fiber-reinforced composites.
- The model developed for predicting the considered responses is fit. Wear tracks, damaged fibers, and matrices are studied through the SEM analysis for the sisal fiber-reinforced composite pins. Ultimately, these composites reduce the adverse effect on the environment.
- The variables considered for the present investigations are only three. By considering more variables, the research is more robust.

References

1. Abilash N, Sivapragash M (2013) Environmental benefits of eco-friendly natural fiber-reinforced polymeric composite materials. International Journal of Application or Innovation in Engineering & Management. 2:53–59
2. Athijayamani A, Ganesamoorthy R, Loganathan KT et al (2016) Modelling and Analysis of the Mechanical Properties of Agave Sisalana Variegata Fibre / Vinyl Ester Composites Using Box-Behnken Design of Response Surface Methodology. Journal of Mechanical Engineering 62(5):273–280
3. Autay R, Missaoui S and J Mars J et.al. Mechanical and tribological study of short glass fiber-reinforced PA 66. Polymers and Polymer Composites 2019; 1–10: DOI: https://doi.org/10.1177/0967391119853956.
4. Ayensu A. Interfacial debonding of natural fiber reinforced composites. *quarterly Science Vision*. 2000; 6(1): 25–34.
5. Badeea Majeed and Suleyman Basturk. Analysis of polymeric composite materials for frictional wear resistance purposes. *Polymers and Polymer Composites* 2020; 1–11: DOI: https://doi.org/10.1177/0967391120903957.
6. Bharath SV, Madhusudhan T (2015) Examination of mechanical and tribological properties of fiber reinforced hybrid composites. International Research Journal of Engineering and Technology 2:124–127
7. Boon Peng Chang, Hazizan Md Akil, Muhammad Ghaddafy Affendy et.al. Comparative study of wear performance of particulate and fiber-reinforced nano-ZnO/ultra-high molecular weight

polyethylene hybrid composites using response surface methodology. *Materials and Design*, 2014; 63: 805–819.
8. Bressan JD, Daros DP, Sokolowski A et al (2007) Influence of hardness on the wear resistance of 17–4 PH stainless steel evaluated by the pin-on-disc testing. Journal of Materials Processing and Technology. 205:353–359
9. Emad Omrani, Pradeep L Menezes and Pradeep K Rohatgi. State of the art on tribological behavior of polymer matrix composites reinforced with natural fibers in the green materials world. *Engineering Science and Technology*. 2016; 19: 717–736.
10. Gupta MK, Srivastava RK (2016) Tribological and dynamic mechanical analysis of epoxy based hybrid sisal/jute composite. Indian Journal of Engineering & Materials Sciences. 23:37–44
11. Hari Om Maurya, Kanishka Jha, and Dr. Y.K. Tyagi. Tribological Behavior of Short Sisal Fiber Reinforced Epoxy Composite. *Polymers and Polymer Composites* 2017; 25(3): 215–220.
12. Ibrahem RA (2016) Friction and Wear Behaviour of Fibre/Particles Reinforced Polyester Composites. International Journal of Advanced Materials Research. 2(2):22–26
13. Irene S Fahim, Salah M Elhaggar and Hatem Elayat. Experimental Investigation of Natural Fiber Reinforced Polymers. *Materials Sciences and Applications*. 2012; 3: 59–66.
14. Palanikumar K, Shadrach Jeya Sekaran A and Pitchandi K. Investigation on mechanical properties of woven alovera/sisal/kenaf fibres and their hybrid composites. *Bull. Mater. Sci.* 2017; 40(1): 117–128.
15. Palanikumar K and Shadrach Jeya Sekaran A. Some natural fibers used in polymer composites and their extraction processes: A review. *Journal of Reinforced Plastics and Composites.* 2014; 33(20): 1879–1892.
16. Mishra P, Acharya SK (2010) Anisotropy abrasive wear behavior of bagasse fiber reinforced polymer composite. Int J Eng Sci Technol 2(11):104–112
17. Rudi Dungani, Myrtha Karina and Subyakto A Sulaeman et.al. Agricultural Waste Fibers Towards Sustainability and Advanced Utilization: A Review. *Asian Journal of Plant Sciences.* 2016; 15(1–2): 42–55.
18. Sahari J, Sapuan SM (2011) Natural Fiber Reinforced Biodegradable Polymer Composites. Rev Adv Mater Sci 30:166–174
19. Shadrach Jeya Sekaran A, Palani Kumar K and Pitchandi K. Evaluation on mechanical properties of woven aloevera and sisal fibre hybrid reinforced epoxy composites. *Bull. Mater. Sci.* 2015; 38(5): 1183–1193.
20. Somen Biswal and Alok Satapathy. Dry sliding wear behavior of epoxy composite reinforced with short palmyra fibers. *IOP Conf. Series: Materials Science and Engineering.* 2016; 115: 1–7: 01202: doi:https://doi.org/10.1088/1757-899X/115/1/012028.
21. Supreeth S, Vinod B, Sudev LJ (2014) Influence of fiber length on the tribological behaviour of short palf reinforced bisphenol- A composite. International Journal of Engineering Research and General Science. 2(4):825–830
22. Thimmana Gouda A et al (2014) Wear study on hybrid natural fiber polymer composite materials used as orthopaedic implants. International Journal of Recent Development in Engineering and Technology. 3(1):25–33
23. Zhong JB, Lv J and Wei C. Mechanical properties of sisal fiber reinforced urea formaldehyde resin composites. *eXPRESS Polymer Letters.* 2007; 1(10): 681–687.

Tribological Characterization of Hybrid Natural Fiber MWCNT Filled Polymer Composites

T. Rajmohan, K. Mohan, R. Prasath, and S. Vijayabhaskar

Abstract Natural fibre reinforced composites packed with Multi Wall Carbon Nanotubes (MWCNTs) are focused by the researchers due to their great tribo and mechanical properties. To ensure collective mechanical and wear qualities, fibre reinforced polymer composites must be hybridised; thus, this study examines the manufacturing and tribological performance of natural fiber-glass reinforced hybrid composites. Compression moulding was used to combine natural fibres like jute, flax, and banana with glass fibre. Particulate MWCNT were disseminated in epoxy resin through ultrasonic bath sonicator, which was then employed as the matrix face for composites reinforced with natural fibre. The sliding wear behaviour of composites reinforced with glass-natural fiber and filled with MWCNT is evaluated using a pin-on-disc wear testing setup. Using D-optimal design, second-order mathematical models were created to forecast particular rate of wear and friction co-efficient by considering wt% of MWCNT, sliding speed load. The surface morphology of worn-out surfaces was studied by SEM analysis.

Keywords Natural fibers · Multi Wall Carbon Nano Tubes (MWCNT) · Scanning electron Microscopy (SEM) · Coefficient of friction · Specific wear rate

1 Introduction

Natural fiber-based composites with outstanding mechanical properties have piqued tribologists' interest, prompting them to research a variety of applications ranging from abrasion materials to abrasion modifiers [1]. Composites which is hybridized are urbanised to accomplish collective properties along with the weighted total of the distinct process through which the individual's valuable excellence can be integrated [2]. Rezghi Maleki investigated the delamination behaviour of flax/epoxy composite laminates. Composites which are reinforced with Natural fiber have excellent capability to substitute glass fiber-reinforced composites [3]. Short fiber (sf)/short

T. Rajmohan (✉) · K. Mohan · R. Prasath · S. Vijayabhaskar
Centre for Composite Science and Technology, Department of Mechanical Engineering, Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya, Enathur, Kanchipuram 631561, India

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_19

fibre, fabric/sf, sf/fillers, fabric/fabric, and fabric/filler are some of the promising reinforcing pair combinations employed in the design of hybrid composites [4].

Maliha et al. investigated, PP composites reinforced with chopped pineapple leaf and banana fibre and their mechanical properties [5]. The hybrid composites with banana and pineapple leaf fibre at a 3:1 ratio have the highest bending modulus, elastic modulus, flexural and tensile strength hardness among the various pineapple leaf and banana fibre ratios. The mechanical distinctive of glass and sisal fibre composites were observed by Palanikumar et al. [6]. The hand layup technique was employed in making the composite laminates. The tensile load of the composite containing 20% sisal fibre and 80% glass fibre is higher than the other. Mechanical and wear conscious of bamboo fibre composite is explored by Seema Jain et al. They have described, that by differentiating the order of fiber orientations the mechanical strength of the composites is found to be increased. This is caused on the impact of strength to weight ratio (high), the composites are said to have a higher resistance to wear [7].

Mohan et al [8] incorporated the MWCNTs in the polymer matrix and it plays a vital role on the influences of the mechanical properties in the composites. Breuer et al. [9] developed ultra-light structured materials with inclusion of MWCNTs as a filler base, in the polymer composites. Such composites shown the enhanced mechanical properties. Anbusagar et al. [10] revealed that the 4% nano clay polyester sandwich composites greatly improved the impact and damage tolerance capability compare to the polystyrene foam-filled composites. Qumrul Ahsan et al. [11]. developed the Mg/SiC and Mg/SiC/MWCNT composites for examining the both distinctive properties of friction and wear. The high friction force is required to deform because of the formation of hard triboflim. The composite incorporated with MWCNT is reducing the friction coefficient than the SiC composite due to the self-lubrication effect of network structured nanotubes. PEEK filled with various weight percentages of nanofillers such as ZrO_2, SiC, SiO_2, Si3N4, and MWCNT was reported by Wang et al. [12]. The inclusion of nanofillers less than 10wt percent infractions improves wear resistance and lowers COF. There were two aspects (Transfer film generation and steel counter surface smoothing) contributed for increased wear and friction coefficient. The superior wear resistance was noted by Zhang et al. [13] because of rolling effect,thermal insulation and well distributed MWCNTs in the matrix. Nanoscale fillers, rather than microscale fillers, have good tribological capabilities, according to Ayman et al. [14]. It is observed that increase of filler concentration which increase the wear resistance as well as co-efficient of friction. Based on the requirements and application, the filler materials are reinforced with the natural fibers to improve the quality and properties of the composites described by Jani et al. [15]

When compared to untreated carbon fibre reinforced composites, Zhang et al. [16] discovered that the treated carbon fibre reinforced composites have a lower COF and wear. Sudhakarmajhi et al. [17] confirmed that modified rice husk composites have better tribological capabilities than untreated rice husk composites. According to Divya et al. [18] while increasing the sliding distances the wear volume is increased, and high SWR is achieved in untreated coir fibre than the alkali treated composites. Srinivasan et al. [19] effectively applied RSM based desirability approach for minimizing the delamination factor in GFR-PP composites drilling. Using Taguchi's orthogonal array, Abhemanyu et al. [21] optimized the wear properties of NFRCs. The specific wear rate of the NFRCs is high at high speeds, which allows for the removal of the required amount of material without burning the fibres. Chang et al. [22] used design of experiments to obtain optimal abrasive performance (wear) of kenaf composites under various sliding considerations. On a pin-on-disc tester, it was discovered that counterface roughness has the greatest impact on wear rate, trailed by applied load, sliding speed, and fibre loading. Fiber loading is the most important element for average COF.

Tribo-materials have a distinctive biography, that includes a variety of mechanical properties, lubrication, friction and wear which are applied in the development of materials for specialised tribological applications. Most manufactured items, such as aerospace seals, bearings, gears, and slideways, are subjected to various applications in the field of tribological testing. From the literature, it is clear that minimum work has been done to find the tribology characteristic of NFRCs impregnate with an MWCNT. In this research work, the natural fibers such as banana, flax and jute fibers are identified, and the composites are fabricated with MWCNT filled epoxy matrix. The tribological behaviour, along with its surface morphologies, are analysed and tested. Modelling and Optimisation are performed by statistical analysis for tribological experiments.

2 Experimental Procedure

2.1 Materials and Methods

Tamilnadu, India. From Sun Tech Fibers, the materials like Matrix (Epoxy; Araldite LY556), Glass fiber and HY951-hardener are procured at Chennai, Tamilnadu, India. MWCNTs acquired from M/s. US Research Nanomaterials Inc, USA were applied as ingredients in producing the composite. Utilising an ultrasonic probe Sonicator, the Nanoparticles with wt percent of 0 percent, 0.5 percent, and 1 percent were equally disseminated into the resin without clustering. Glass fibres were put at the crest and base of the composite, whereas natural fibres were organised sequentially. The composites were made with a 10:1 mixture of modified epoxy and hardener by using a compression moulding process. [4] Table 1 shows the composition of composites that have been fabricated and Fig. 1 shows the fabricated composites.

The microstructure of prepared nanocomposites was done using a Scanning Electron Microscope. From Fig. 2a it is observed that the reinforcements are well bonded with the nano filled matrix which meliorate the mechanical characteristics [23] and attire resistance of the composites. In due with the presence of OH group on the banana surface, which is firmly adhered to the matrix phase [24] confirming that no fracture had found on fiber interfaces. Figure 2b reveals, uniform distribution of nano filled matrix into the reinforcement also confirmed the compatibiliser adhere

Table 1 Composition of natural fibre-glass reinforced composites

Process parameter	Code	Factor	Levels		
			1	2	3
Sliding Speed in m/s	S	Numerical	500	1000	1500
Load in N	P	Numerical	5	10	15
Wt.% of MWCNT	W	Numerical	0	0.5	1
Natural Fiber	M	Categorical	Flax	Jute	Banana

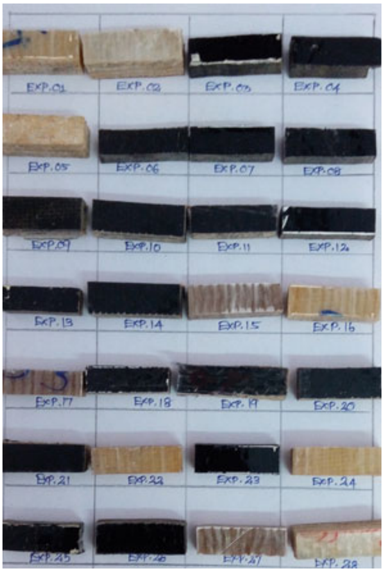


Fig. 1 Prepared Tribo nano composites

to the fiber cells which increase the interfacial adhesion between reinforcement and matrix. Figure 2c indicates the good distribution of MWCNT into the matrix without forming any nanoclusters, which leads to enhance the resistance of wear [13] and increase the cohesive coupling between the matrix and reinforcements.

BY utilizing the carl ZEISS device, the XRD analysis of the fabricated composites and their diffraction pattern was found. All XRD patterns were equal to conventional XRD patterns, and all phases present in the composite were recognised. The examination was carried out at a 2 min interval. The findings of the XRD examination for the 1wt percent MWCNT filled natural fibre composites are presented in Fig. 3. The presence of cellulose in the composites was confirmed by interference peaks at 2 teta = 13.3750 (pasture within 12 and 15) based on the plot and XRD pattern. According to earlier study, this peak reflects with intensity when amorphous components like amorphous cellulose, hemicelluloses, pectin, lignin and rise in fibres and become dirty in diffractograms. However, when natural fibres have a large percentage

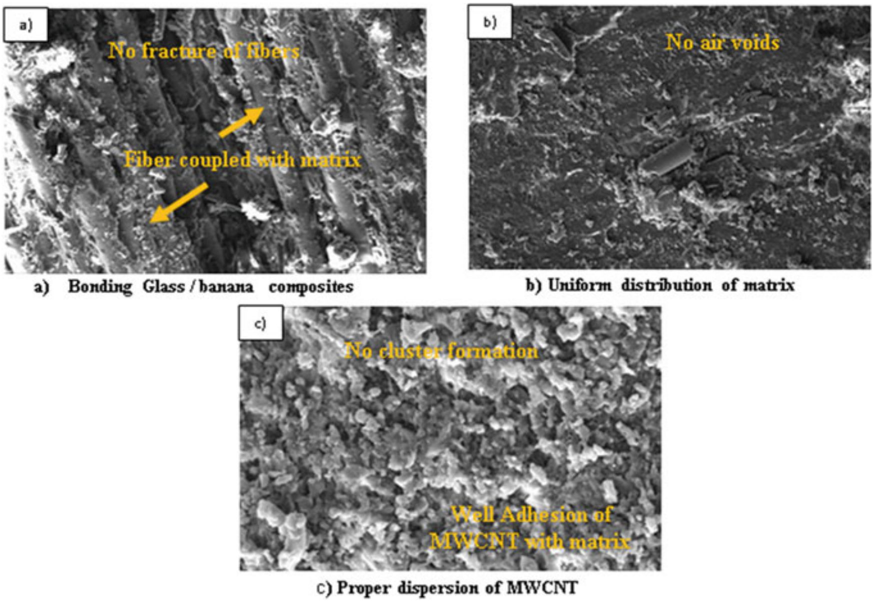


Fig. 2 Microstructure of fabricated nano composites

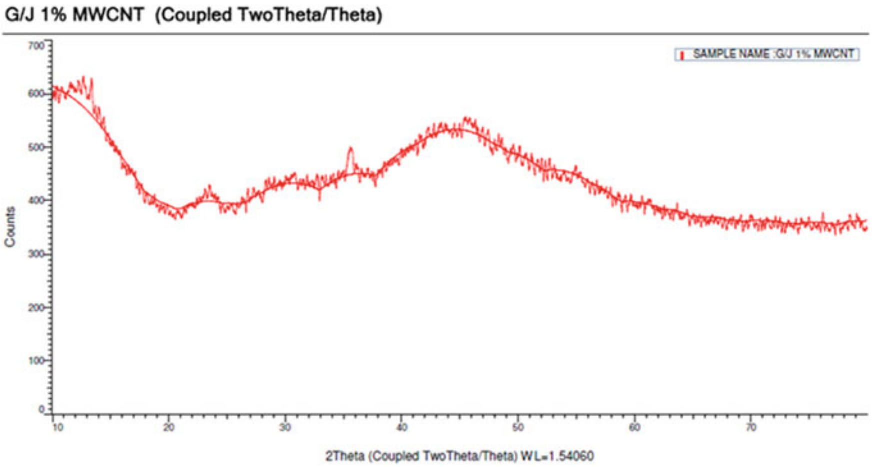


Fig. 3 Image of XRD analysis of 1wt% MWCNT composite

of crystalline cellulose, the peak reflected in diffractograms is clearly defined and precise [2, 26].

Table 2 Design of wear parameters and their levels

Specimen	Wt. % of Epoxy	Wt. % of Glass	Wt % of MWCNT	Wt. % of Banana	Wt. % of Jute	Wt. % of Flax
A1, A2 & A3	60	25	0, 0.5 &1	15	–	–
B1, B2 & B3	60	25	0, 0.5 &1	–	15	–
C1, C2 & C3	60	25	0, 0.5 &1	–	–	15

2.2 Experimental Design

The experiments in the present investigation are meant to develop and analyse the performance of glass-NFRCs in dry sliding wear, such as the SWR and COF, using D-optimal design. Normal factorial, or fractional factorial, designs need many runs for the resources or time available for the experiment, and the design space is limited [27], leading to the use of D-optimal designs as an alternative to traditional designs. Table 2 presents the design plan, which includes three numerical components with three degrees of variation and one categorical factor with three levels of variation.

2.3 Experimental Procedure

Dry sliding wear testing for glass-NFRCs were carried out on the pin-on-disc machine model [27]. The schematic arrangement of the overall experiment plan is presented in Fig. 4. The glass-natural fiber reinforced composites were machined into a square pin of size 8X8X10 mm. The pin is alleged fixed against the opposing 316 SS comprising hardness HRC 65. The specimen was separated and dirt-free with acetone after operating at a continuous fixed sliding distance. A digital balance with a minimum count of 1 mg was used to calculate the weight reduction. The particular wear rate is calculated using the calculation below (SWR).

$$\frac{Volumeloss}{SlidingdistanceXLoad}\text{Specificwearrate} = \frac{Volumeloss}{SlidingdistanceXLoad} mm^3/Nm \quad (1)$$

With software that comes with the equipment, the COF is measured immediately. Table 3 shows the results of 28 experiments conducted using the D-optimal design.

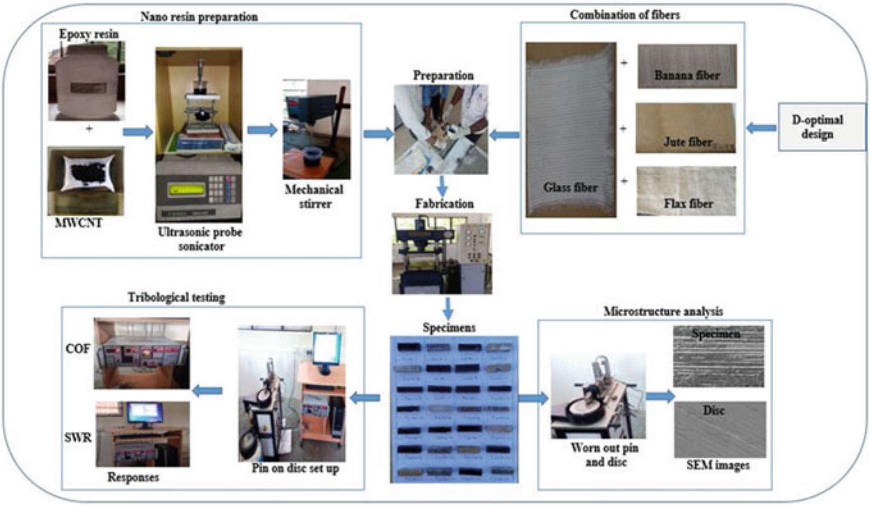


Fig. 4 Schematic layout of processing

3 Results and Discussion

3.1 Investigation of Extended Wear Models

Wear test has been executed with respect to the planned design matrix including friction co-efficient and specific wear rate were deliberated. Design expert 7.0.0™ statistical software has opted for numerical analysis, quadratic model building, and to examine the persuade to wear process parameters. The adequacies of formulated wear data are explored using analysis of variance (ANOVA), and the implication in the proposed models are assessed through F-test. The ANOVA details for SWR and COF are shown in Tables 1 and 2, respectively.

The test for lack of fit and significance were used to assess the suitability of wear models. It is observed from the tables that $p < 0.05$, indicating that the established models are significant at 95% confidence level. Likewise, the multiple regression coefficients for determination (R2) for SWR and COF are also found to be 0.986 and 0.998, respectively. The multiple regression co-efficient for generated models approaches unity, indicating that the response model fits the actual data best and that the difference between anticipated and actual data is minimal. The model F value denotes that the models are substantial. Certain terms can be regarded as immaterial terms based on the created models because their “Prob. > F.“ value is more than 0.05. The basic expressions are preserved after the immaterial terms are removed using the backwards elimination selection procedure. The quadratic models to predict COF and SWR for composites reinforced with flax, jute and banana fiber are presented in Tables 6 and 7.

Table 3 Experimental design and results of D-optimal design

Run	Sliding Speed (m/s)	Load (Kg)	MWCNT (%)	Fiber	Specific Wear Rate (mm3/Nm)	Coefficient of friction
1	500	15	0	Flax	8.86E-05	0.207
2	500	5	0	Banana	7.27E-05	0.123
3	500	15	1	Jute	5.06E-05	0.206
4	1000	7.5	0.75	Jute	3.11E-05	0.143
5	1000	15	0	Banana	3.68E-05	0.168
6	500	10	1	Flax	3.73E-05	0.203
7	1500	10	1	Jute	3.23E-05	0.285
8	500	15	1	Jute	5.05E-05	0.199
9	1250	10	0.25	Jute	5.11E-05	0.105
10	1500	15	1	Banana	1.24E-05	0.275
11	1500	5	0.5	Banana	3.54E-05	0.031
12	1500	5	1	Flax	2.11E-05	0.227
13	1000	5	0.5	Flax	1.73E-05	0.134
14	500	15	1	Banana	5.93E-05	0.233
15	1000	5	0	Jute	2.10E-05	0.188
16	1500	10	0	Flax	1.24E-05	0.102
17	500	10	0	Jute	8.70E-05	0.118
18	750	10	0.5	Banana	6.75E-05	0.057
19	500	5	1	Jute	8.90E-07	0.165
20	1000	5	1	Banana	3.16E-05	0.238
21	1000	5	1	Banana	3.68E-05	0.235
22	1250	10	0.75	Flax	3.16E-05	0.107
23	500	10	1	Flax	2.49E-05	0.194
24	1500	10	0	Flax	1.69E-05	0.094
25	1000	15	0.5	Flax	5.88E-05	0.077
26	1500	15	1	Flax	2.91E-05	0.178
27	1500	15	0	Jute	7.86E-05	0.183
28	1000	15	0	Banana	3.01E-05	0.175

The residuals' normal probability graphs are shown in Fig. 5. The regression model is acceptable and adequate indicated by the errors that are normally dispersed from plotting the residuals for all responses over a straight line. This indicates that the constructed second order quadratic models are acceptable in capturing the process.

Table 4 ANOVA for Specific wear rate

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.44E-08	17	8.45E-10	42.9	< 0.0001	Significant
A-Sliding Speed	2.74E-09	1	2.74E-09	139.3	< 0.0001	
B-Load	1.88E-09	1	1.88E-09	95.5	< 0.0001	
C-MWCNT	1.59E-09	1	1.59E-09	80.6	< 0.0001	
D-Fibre	7.63E-10	2	3.82E-10	19	0.0004	
AB	1.66E-10	1	1.66E-10	8.4	0.0157	
AC	1.39E-09	1	1.39E-09	70.6	< 0.0001	
AD	1.15E-09	2	5.74E-10	29.2	< 0.0001	
BC	4.66E-10	1	4.66E-10	23.6	0.0007	
BD	2.11E-09	2	1.05E-09	53.5	< 0.0001	
CD	1.27E-09	2	6.35E-10	32.29	< 0.0001	
A^2	6.31E-10	1	6.31E-10	32.11	0.0002	
B^2	2.86E-12	1	2.86E-12	0.145	0.7107	
C^2	9.45E-10	1	9.45E-10	48.09	< 0.0001	
Residual	1.97E-10	10	1.97E-11			
Lack of Fit	7.36E-11	5	1.47E-11	0.599	0.7062	Not significant
Pure Error	1.23E-10	5	2.46E-11			
Cor Total	1.46E-08	27				

3.2 Effect of Tribological Parameters on Performances

3.2.1 Specific Wear Rate

In Fig. 6, a 2-D contour plot depicted the cause of load, sliding speed, and the weight percent of MWCNT on SWR. Because of the polymeric coating generated on the counter steel disc, the specific wear rate decreased at high wear parameter settings [28]. This film structure transforms hard metallic material into soft polymeric substance [1]. According to Friedrich et al. [29], increasing the applied load raises the particular wear rate. The presence of the transfer layer is advantageous since it reduces friction and wear through defensive shielding. The wear performance of transfer layers is influenced by transfer layer cohesive bonds, layer thickness and bond strength [28]. MWCNT build-up in the polymer matrix results in increased wear resistance. MWCNT enhances the mechanical and thermal conductivity considerably the NFRCs [1]. The wear resistance is increased when MWCNT crumble and engender reaction goods which increases the bonding between the polymer film and the steel disc [29].

Table 5 ANOVA for coefficient of friction

Source	Sum of squares	df	Mean square	F Value	p-value Prob > F	
Model	0.111768	17	0.006575	387.3214	< 0.0001	Significant
A-Sliding Speed	0.000157	1	0.000157	9.245436	0.0124	
B-Load	0.001145	1	0.001145	67.46933	< 0.0001	
C-MWCNT	0.02616	1	0.02616	1541.13	< 0.0001	
D-Fibre	0.001822	2	0.000911	53.65672	< 0.0001	
AB	3.58E-05	1	3.58E-05	2.107566	0.1772	
AC	0.00653	1	0.00653	384.7024	< 0.0001	
AD	0.013693	2	0.006846	403.326	< 0.0001	
BC	0.000192	1	0.000192	11.32959	0.0072	
BD	0.006024	2	0.003012	177.4555	< 0.0001	
CD	0.004028	2	0.002014	118.6528	< 0.0001	
A^2	0.003729	1	0.003729	219.6987	< 0.0001	
B^2	0.002466	1	0.002466	145.275	< 0.0001	
C^2	0.03702	1	0.03702	2180.926	< 0.0001	
Residual	0.00017	10	1.7E-05			
Lack of Fit	4.37E-05	5	8.75E-06	0.347184	0.8648	Not significant
Pure Error	0.000126	5	2.52E-05			
Cor Total	0.111938	27				

3.2.2 Coefficient of Friction

In Fig. 7, the influence of weight % of MWCNT, load and sliding speed on COF is displayed through a 2-D response surface plot. During increased sliding circumstances, the COF rises. As the stress increases, the contact asperities bend elastically and plastically, increasing the true contact area [30]. This increment in the true contact area as a result of asperity crumple which control friction coefficient [26]. Owing to outstanding features like high aspect ratio, adding MWCNT to the epoxy reduces the COF and improves wear resistance. It also improves thermal deterioration limit, thermal conductivity and mechanical strength. It has also been demonstrated that the inclusion of MWCNTs increases COF wear performance [31]. The rolling effect of MWCNT and thermal insulation behaviour could be accredited to superior wear resistance owing to well-distributed MWCNTs in the matrix [32]. Due to the creation of a transfer layer on the counter face, the friction coefficient is constantly lowering. Improved friction properties were reported even at greater loading as a result of the improvement in the adhesion at the matrix—filler interface and the dissolution of agglomeration [29].

Table 6 Quadratic Equation for Categorical factors on specific wear rate

Flax	$5.73193 \times 10^{-5} - 1.43042 \times 10^{-7} \times Sliding\ Speed + 7.37141 \times 10^{-6} \times Load + 5.29915 \times 10^{-5} \times MWCNT - 1.84649 \times 10^{-9} \times Sliding\ Speed \times Load + 4.28346 \times 10^{-8} \times Sliding\ Speed \times MWCNT - 2.67792 \times 10^{-6} \times Load \times MWCNT + 5.72044 \times 10^{-11} \times Sliding\ Speed^2 - 3.16617 \times 10^{-8} \times Load^2 - 7.82752 \times 10^{-5} \times MWCNT^2$
Jute	$6.07347 \times 10^{-5} - 1.33387 \times 10^{-7} \times Sliding\ Speed + 9.09242 \times 10^{-6} \times Load + 2.37978 \times 10^{-5} \times MWCNT - 1.84649 \times 10^{-9} \times Sliding\ Speed \times Load + 4.28346 \times 10^{-8} \times Sliding\ Speed \times MWCNT - 2.67792 \times 10^{-6} \times Load \times MWCNT + 5.72044 \times 10^{-11} \times Sliding\ Speed^2 - 3.16617 \times 10^{-8} \times Load^2 - 7.82752 \times 10^{-5} \times MWCNT^2$
Banana	$0.000132853 - 1.78243 \times 10^{-7} \times Sliding\ Speed + 3.80404 \times 10^{-6} \times Load + 6.27029 \times 10^{-5} \times MWCNT - 1.84649 \times 10^{-9} \times Sliding\ Speed \times Load + 4.28346 \times 10^{-8} \times Sliding\ Speed \times MWCNT - 2.67792 \times 10^{-6} \times Load \times MWCNT + 5.72044 \times 10^{-11} \times Sliding\ Speed^2 - 3.16617 \times 10^{-8} \times Load^2 - 7.82752 \times 10^{-5} \times MWCNT^2$

Table 7 Quadratic Equation for Categorical factors on Co efficient of friction

Flax	$0.310356372 + 0.00017394 \times \mathit{Sliding\ Speed} - 0.024010461 \times \mathit{Load} - 0.565724068 \times \mathit{MWCNT} - 8.57328 \times 10^{-7} \times \mathit{Sliding\ Speed} \times \mathit{Load} + 9.29109 \times 10^{-5} \times \mathit{Sliding\ Speed} \times \mathit{MWCNT} + 0.001720655 \times \mathit{Load} \times \mathit{MWCNT} - 1.39043 \times 10^{-7} \times \mathit{Sliding\ Speed}^2 + 0.000929366 \times \mathit{Load}^2 + 0.48984357 \times \mathit{MWCNT}^2$
Jute	$0.067488748 + 0.000319667 \times \mathit{Sliding\ Speed} - 0.016139208 \times \mathit{Load} - 0.51321749 \times \mathit{MWCNT} - 8.57328 \times 10^{-7} \times \mathit{Sliding\ Speed} \times \mathit{Load} + 9.29109 \times 10^{-5} \times \mathit{Sliding\ Speed} \times \mathit{MWCNT} + 0.001720655 \times \mathit{Load} \times \mathit{MWCNT} - 1.39043 \times 10^{-7} \times \mathit{Sliding\ Speed}^2 + 0.000929366 \times \mathit{Load}^2 + 0.489843574 * \mathit{MWCNT}^2$
Banana	$0.088743605 + 0.000239173 \times \mathit{Sliding\ Speed} - 0.014220432 \times \mathit{Load} - 0.491300789 \times \mathit{MWCNT} - 8.57328 \times 10^{-7} \times \mathit{Sliding\ Speed} \times \mathit{Load} + 9.29109 \times 10^{-5} \times \mathit{Sliding\ Speed} \times \mathit{MWCNT} + 0.001720655 \times \mathit{Load} \times \mathit{MWCNT} - 1.39043 \times 10^{-7} \times \mathit{Sliding\ Speed}^2 + 0.000929366 \times \mathit{Load}^2 + 0.489843574 \times \mathit{MWCNT}^2$

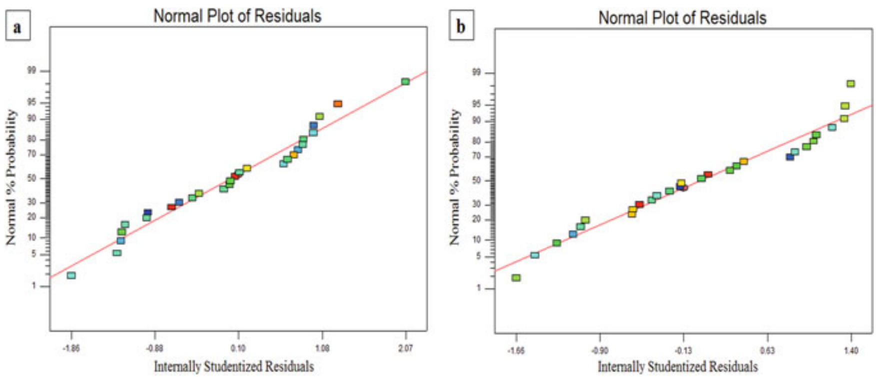


Fig. 5 Normal probability plots for: **a** specific wear rate, and **b** coefficient of friction

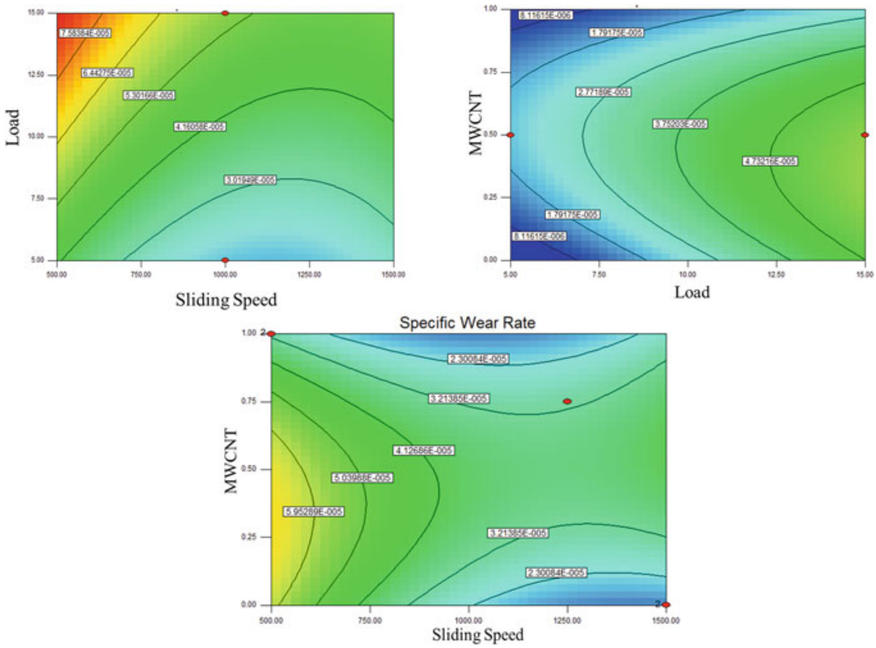


Fig. 6 Effect of wear parameters on specific wear rate as 2D contour plot

3.3 Effect of Natural Fibers on Performances

The effect of categorical factors on responses mainly frictional coefficient and specific wear rate were presented in Fig. 8 and 9. The banana fibers show better performances for all sliding conditions compared with other natural fibers. The superior performance of banana fibres is attributable to high tensile modulus and strength low

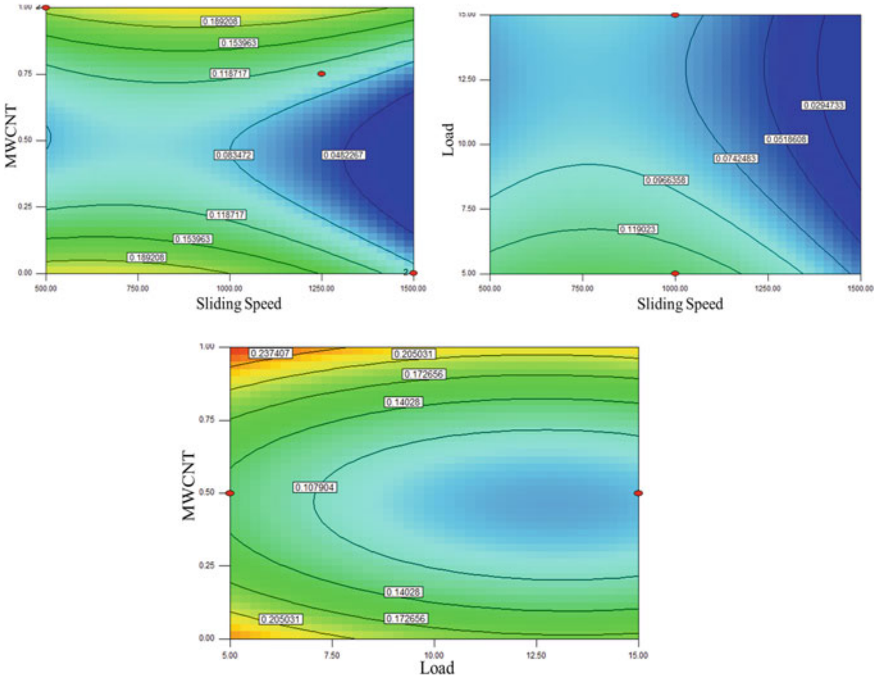


Fig. 7 Effect of wear parameters on COF as 2D contour plot

elongation at break and low density [33]. The high cellulose content of banana fibre composites resulted in low abrasive damage to processing equipment, that can be accredited to the fibres' soft nature [31].

After descending under various settings, SEM micrographs of the banana–glass composite demonstrate that many fibres are still unaffected, without any separation or fibre pull out, demonstrating that banana fibres have a high weight carrying capacity. Furthermore, banana demonstrated a drop-in border temperature, which is attributed to banana fibres' ability to buckle effectively under adhesive descending settings, reducing the influence of synthetic resin thermo-mechanical loading [31].

3.4 Multi-response Optimisation of Wear Parameters Using Desirability Analysis

The RSM-based desire function approach is used in this study to optimise the compound performance of wear parameters. The concurrent optimisation strategy proposed by Derringer and Suich is one constructive way to compound response optimization [34] The DESIGN-EXPERT® package is used to create the optimisation analysis. Table 7 shows the aim that was set, the lower and maximum limits that

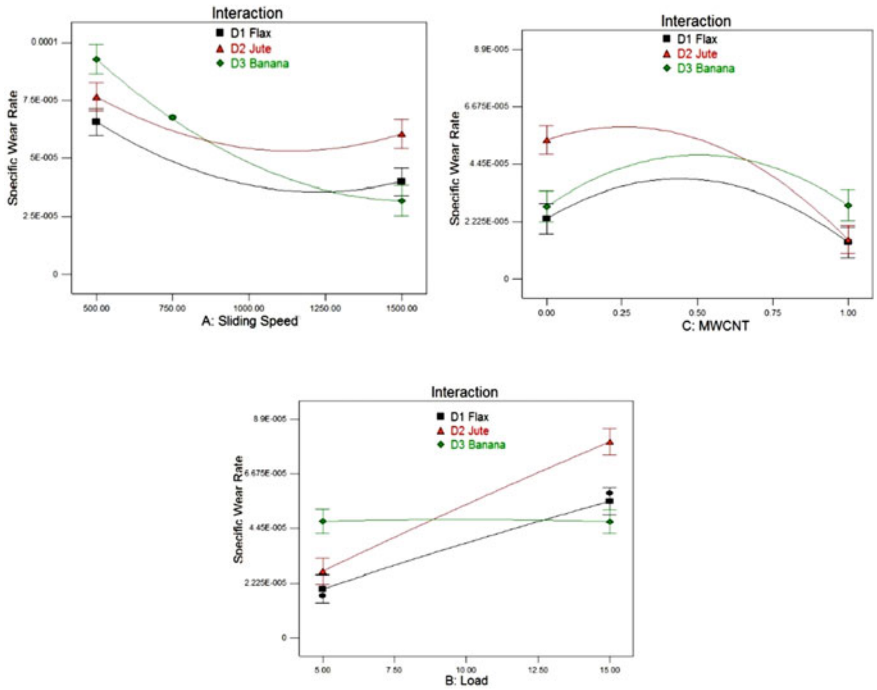


Fig. 8 Effect of categorical factors on response on specific wear rate

were used, the weights that were used, and the relevance of the criteria that were given. Different optimum solutions are found using a desirability-based methodology. The solution with the highest level of attractiveness is selected. Table 8 shows the best solution discovered for the Optimisation. Desirability is a scale based on the closeness of response ranging between 0 and 1.

4 Confirmation Experiments

The generated models are validated through confirmation studies in addition to statistical validation. Table 9 contains the details of the confirmation experiments. The confirmation experiments are carried out twice, with mean being utilised in both cases. The predicted values are pretty near to the findings of the investigation. Hence the developed technique is fit to enhance the performance of hybrid natural fiber reinforced nanocomposites.

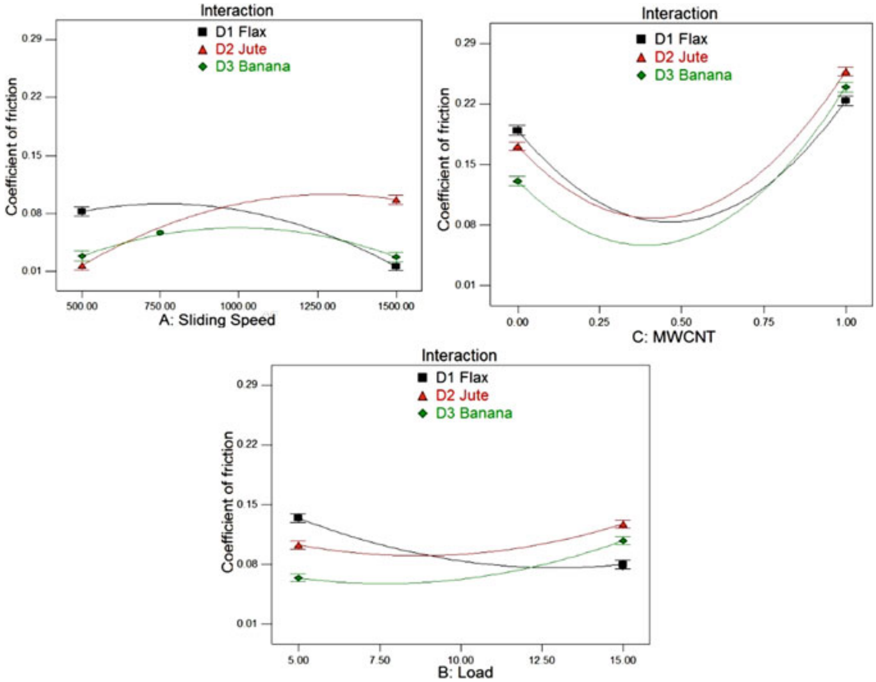


Fig. 9 Effect of categorical factors on response on co-efficient of friction

Table 8 Constraints used in desirability analysis

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Sliding Speed	is in range	500	1500	1	1	3
Load	is in range	5	15	1	1	3
MWCNT	is in range	0	1	1	1	3
Fibre	is in range	Flax	Banana	1	1	3
Specific Wear Rate	minimize	8.9E-07	8.86E-05	1	1	3
Coefficient of friction	minimize	0.031	0.285	1	1	3

Table 9 Results of desirability analysis

No	Sliding Speed	Load	MWCNT	Fibre	Specific Wear Rate	Coefficient of friction	Desirability	
1	1500	7.7	0.06	Banana	6.82E-06	0.050554	0.927715	Selected
2	1500	7.75	0.06	Banana	6.42E-06	0.051709	0.92769	
3	1500	7.85	0.06	Banana	6.76E-06	0.050745	0.92768	

Table 10 Confirmation experiments and results

	Optimal machining parameter	
	Prediction	Experimental
Setting level	Sliding speed = 1500 Load = 7.7 N Wt. % MWCNT = 0.05 Fiber type = Banana	
Specific wear rate	6.82E-06	7.161E-06
Coefficient of friction	0.050554	0.053082

5 Wear Mechanism

SEM pictures of natural fibre reinforced composite specimens following wear testing are shown in Fig. 10a–f.

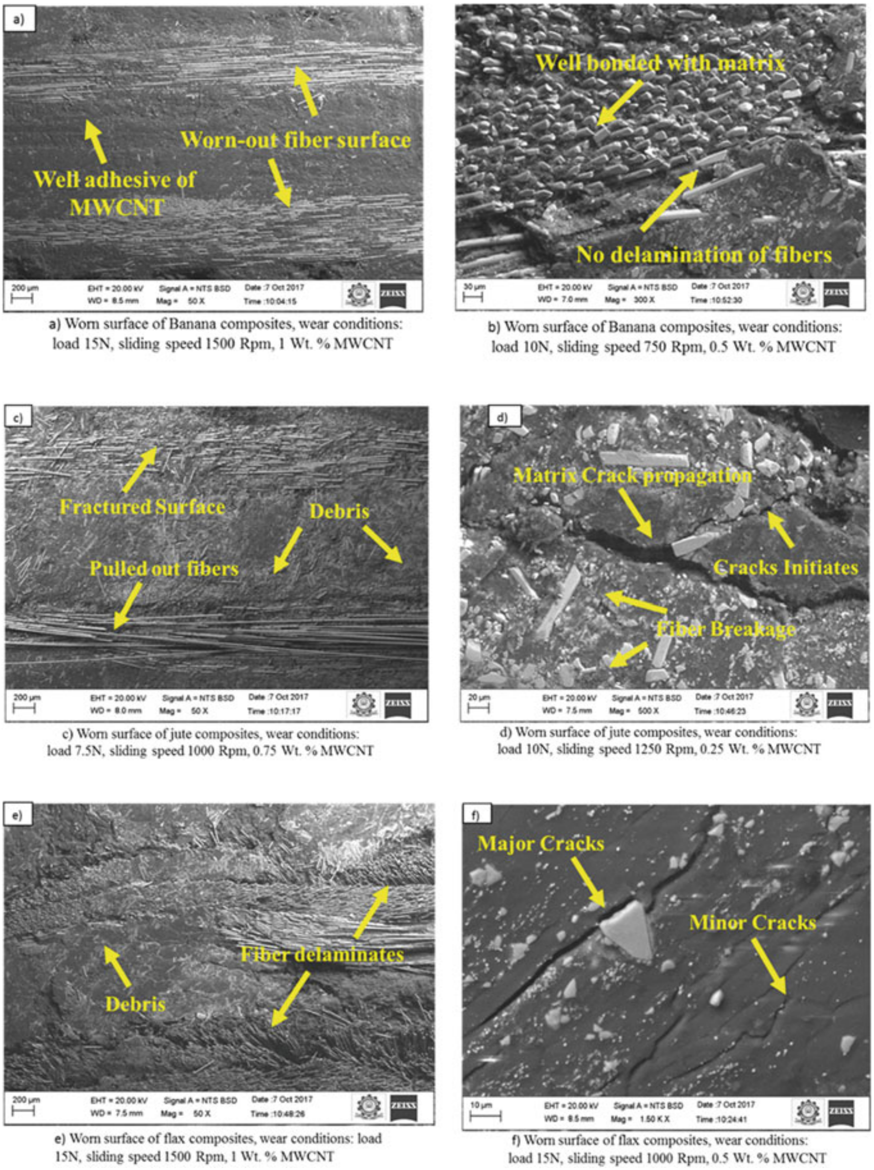
Debonding is seen in all of the specimens in a significant amount. The specimens also showed fibre fracture, fibre pull out, and matrix breakdown [35] SEM was used to examine the effect of the wear mechanism on wear characteristics, as illustrated in Fig. 11a, b.

A collection of polymer wreckage is known to cling to the steel disc's surface and get bonded to it. This indicates that wear over the composites' surface occurred due to adhesion, resulting in a dense and irregular film transfer over the Steel disc. The incorporation of MWCNTs, on the other hand, could adequately diminish the bond among the steel disc's surface and composites [36].

6 Conclusion

The tribological behavior of MWCNT filled natural-glass fiber composites on specific wear rate, and COF is evaluated using D-optimal design. The following are the key findings of this investigation:

- The MWCNT-filled Natural fibers like banana, flax and jute were hybridised with glass fiber using compression moulding technique, and the wear specimens have prepared.
- The wear performances of natural fibre reinforced MWCNT-filled composites were examined at various applied loads, speeds, and MWCNT weight percent under dry sliding conditions.
- Using RSM-based D-optimal design, quadratic models were developed to analyse the performances of natural fibre reinforced MWCNT-filled composites in dry sliding wear. The created model's appropriateness was tested using ANOVA.
- To optimise dry sliding wear characteristics of composites, RSM-based desirability analysis is used. According to the optimisation results, a sliding speed of 1500 rpm, a load of 7.7 N, a weight percent of MWCNT of 0.06 percent, and a



a) Worn surface of Banana composites, wear conditions: load 15N, sliding speed 1500 Rpm, 1 Wt. % MWCNT

b) Worn surface of Banana composites, wear conditions: load 10N, sliding speed 750 Rpm, 0.5 Wt. % MWCNT

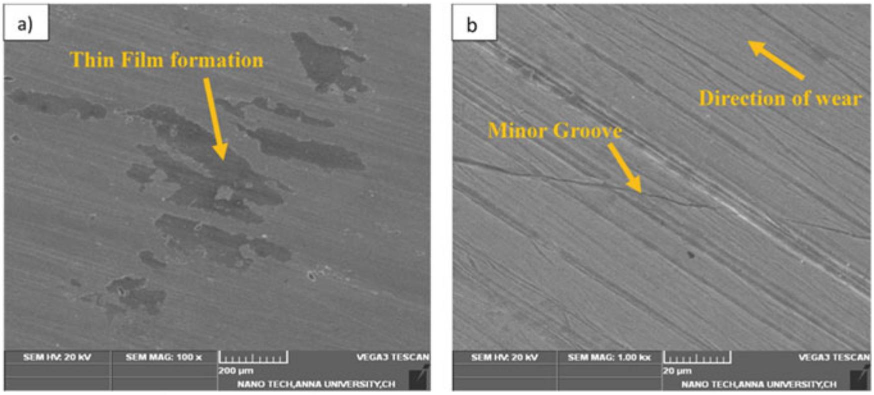
c) Worn surface of jute composites, wear conditions: load 7.5N, sliding speed 1000 Rpm, 0.75 Wt. % MWCNT

d) Worn surface of jute composites, wear conditions: load 10N, sliding speed 1250 Rpm, 0.25 Wt. % MWCNT

e) Worn surface of flax composites, wear conditions: load 15N, sliding speed 1500 Rpm, 1 Wt. % MWCNT

f) Worn surface of flax composites, wear conditions: load 15N, sliding speed 1000 Rpm, 0.5 Wt. % MWCNT

Fig. 10 SEM micrograph of the worn-out surfaces of nano composites



a) Fractured and discontinues polymer film on counter surface

b) The direction of wear

Fig. 11 SEM micrograph of the counterpart surfaces

fibre type of banana is preferable to minimize the COF and specific wear rate of composites under dry sliding conditions.

- Superior friction qualities were reported even at increased loading owing to improved interfacial adhesion between the matrix and filler, agglomeration and disintegration.
- The morphology of the worn surface was observed through SEM. The SEM investigations revealed that all of the specimens have significant debonding. In the specimens, fibre fracture, fibre pull out, and matrix breakage have all been detected.
- MWCNTs significantly reduce adhesive wear, which was a benefit of generating a thin transfer film, enhancing wear resistance and lowering the COF.

Symbols and Abbreviations

Natural Fiber Reinforced Composites	NFRCs
Multiwalled carbon Nanotube	MWCNT
Scanning Electron Microscope	SEM
XRD	X Ray Difraction
SWR	Specific wear rate
COF	Co Efficient of Friction
Analysis of variance	ANOVA

References

1. Karthikeyan S, Rajini N, Jawaid M, Winowlin Jappes JT, Thariq MT, Siengchin S, Sukumaran J, (2017), A review on tribological properties of natural fiber based sustainable hybrid composite. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Dec;231(12):1616–34.
2. Ramesh M, Palanikumar K, Reddy KH, (2013), Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites, Composites Part B: Engineering, May 1;48:1–9.
3. Rezghi Maleki H, Hamedi M, Kubouchi M, Arao Y,(2019), Experimental investigation on drilling of natural flax fiber-reinforced composites, Materials and Manufacturing Processes, Feb 17;34(3):283–92.
4. Mohan K, Rajmohan T, (2017), Fabrication and characterization of MWCNT filled hybrid natural fiber composites, Journal of Natural Fibers, Nov 2;14(6):864–74
5. Rahman M, Das S, Hasan M, (2018), Mechanical properties of chemically treated banana and pineapple leaf fiber reinforced hybrid polypropylene composites, Advances in Materials and Processing Technologies, Oct 2;4(4):527–37.
6. Palanikumar K, Ramesh M, Hemachandra Reddy K, (2016), Experimental investigation on the mechanical properties of green hybrid sisal and glass fiber reinforced polymer composites, Journal of Natural Fibers, May 3;13(3):321–31.
7. Jain S, Kumar R, (1994), Processing of bamboo fiber reinforced plastic composites. Material and Manufacturing Process, Aug 1;9(5):813–28.
8. Mohan K, Rajmohan T, (2018), Effects of MWCNT on mechanical properties of glass-flax fiber reinforced nano composites, Materials Today: Proceedings, Jan 1;5(5):11628–35.
9. Breuer O, Sundararaj U, (2004), Big returns from small fibers: a review of polymer/carbon nanotube composites, Polymer composites. Dec;25(6):630–45.
10. Anbusagar NRR, Palanikumar K (2018) Nanoclay Addition and Core Materials Effect on Impact and Damage Tolerance Capability of Glass Fiber Skin Sandwich Laminates. Journal of Silicon 10(3):769–779. https://doi.org/10.1007/s12633-016-9529-2
11. Ahsan Q, Tee ZW, Rahmah S, Chang SY, Warikh M, (2016), Wear and friction behaviour of magnesium hybrid composites containing silicon carbide and multi-walled carbon nanotubes, Advances in Materials and Processing Technologies, Apr 2;2(2):303–17.
12. Wang Q-H, Qun-JiXue W-M, Chen J-M (2000) Effect of Nanometer SiC Filler on the Tribological Behavior of PEEK under Distilled Water Lubrication. J Appl Polym Sci 78(3):609–614. https://doi.org/10.1002/1097-4628(20001017)78:33.0.CO;2-D
13. Hui-juan Zhang, Zhao-Zhu Zhang, Fang Guo, Kun Wang, (2009), Enhanced wear properties of hybrid PTFE/cotton fabric composites filled with functionalised multi-walled carbon nanotubes, Materials Chemistry and Physics, 2009, 116(1),183–190. DOI: https://doi.org/10.1016/j.matchemphys.2009.03.008.
14. Aly AA, Zeidan ES, Alshennawy AA, El-Masry AA, Wasel WA, (2012), Friction and wear of polymer composites filled by nano-particles: a review. World Journal of Nano Science and Engineering, Mar 28;2(01):32.
15. Jani S.P. Senthil Kumar, (2018), A Adam Khan. M Uthaya Kumar M. Machinability of hybrid natural fiber composite with and without filler as reinforcement, Materials and Manufacturing Processes, DOI: https://doi.org/10.1080/10426914.2015.1117633.
16. Zhang XR, Pei XQ, Wang QH, (2007), The effect of fiber oxidation on the friction and wear behaviors of short-cut carbon fiber/polyimide composites, Express Polymer Letters, May 1;1(5):318–25.
17. Majhi S, Samantarai SP, Acharya SK, (2012), Tribological behavior of modified rice husk filled epoxy composite. International Journal of Scientific & Engineering Research, Jun;3(6):180–4.
18. Divya GS, Kakhandaki A, Suresha B (2014) Wear behaviour of coir reinforced treated and untreated hybrid composites. International Journal of Innovative Research and Development 3(5):632–639

19. Rajmohan T, Palanikumar K, (2013), Modeling and analysis of performances in drilling hybrid metal matrix composites using D-optimal design, The International journal of advanced Manufacturing technology, Feb 1;64(9–12):1249–61.
20. Srinivasan T, Palanikumar K, Rajagopal K, Latha B (2017) Optimisation of Delamination Factor in Drilling GFR-Polypropylene Composites. Mater Manuf Processes. https://doi.org/10.1080/10426914.2016.1151038
21. Abhemanyu PC, Prassanth E, Navin Kumar T, Vidhyasagar R, Prakash Marimuthu K (2018) Wear Properties of Natural Fiber Composite Materials. AIP Conf Proc. https://doi.org/10.1063/1.5092889
22. Chang BP, Yong YF, Md Akil H, Md Nasir R, Optimization on Abrasive Wear Performance of Pultruded Kenaf-Reinforced Polymer Composite Using Taguchi Method. KEM https://doi.org/10.4028/www.scientific.net/kem.739.42.
23. Rajmohan T, Mohan K, Palanikumar K (2015) Synthesis and characterisation of Multi Wall Carbon Nano tube (MWCNT) filled hybrid banana-glass fiber reinforced composites. Appl Mech Mater 766:193–198
24. Biswal M, Mohanty S, Nayak SK, (2012), Banana fiber-reinforced polypropylene nanocomposites: Effect of fiber treatment on mechanical, thermal, and dynamic-mechanical properties, Journal of Thermoplastic Composite Materials, Sep;25(6):765–90.
25. Jayaramudu J, Guduri BR, Rajulu AV, (2010), Characterization of new natural cellulosic fabric Grewia tilifolia. Carbohydrate polymers, Mar 17;79(4):847–51.
26. Bajpai PK, Singh I, Madaan J, (2013), Tribological behavior of natural fiber reinforced PLA composites, Wear, Jan 15;297(1–2):829–40.
27. Rajmohan T, Palanikumar K, Davim JP, Premnath AA, (2016), Modeling and optimization in tribological parameters of polyether ether ketone matrix composites using D-optimal design Journal of Thermoplastic Composite Materials, Feb;29(2):161–88.
28. Shang Y, Wu X, Liu Y, Jiang Z, Wang Z, Jiang Z, Zhang H, (2019), Preparation of PEEK/MWCNTs composites with excellent mechanical and tribological properties, High Performance Polymers, Feb;31(1):43–50.
29. Friedrich K, Karger-Kocsis J, Lu Z (1991) Effect of steel counterface roughness and temperature on the friction and wear of PEEK composites under dry sliding conditions. Wear 148(2):235–247. https://doi.org/10.1016/0043-1648(91)90287-5
30. Ahmed KS, Khalid SS, Mallinatha V, Kumar SA, (2012) Dry sliding wear behavior of SiC/Al2O3 filled jute/epoxy composites, Materials & Design (1980–2015), Apr 1;36:306–15.
31. Zhang H-J, Zhang Z-Z, Guo F, Jiang W (2009) Study on the tribological behavior of hybrid PTFE/cotton fabric composites filled with Sb2O3 and melamine cyanurate. Tribol Int. https://doi.org/10.1016/j.triboint.2009.03.002
32. Dixit S, Verma P (2012) The effect of hybridisation on mechanical behaviour of coir / sisal / jute fibers reinforced polyester composite material. Research Journal of Chemical Sciences 2(6):91–93
33. Maleque MA, Belal FY, Sapuan SM, (2007), Mechanical properties study of pseudo-stem banana fiber reinforced epoxy composite, The Arabian journal for science and engineering, Oct 1;32(2B):359–64.
34. Derringer G, Suich R, (1980), Simultaneous optimization of several response variables, Journal of quality technology, Oct 1;12(4):214–9.
35. Nirmal U, Hashim J, Ahmad MM, (2015), A review on tribological performance of natural fiber polymeric composites, Tribology International, Mar 1;83:77–104.
36. Kumar D, Rajmohan T, Experimental investigation of wear of multiwalled carbon nanotube particles filled poly-ether-ether ketone matrix composites under dry sliding. Journal of Thermoplastic Composite Materials.https://doi.org/10.1177/0892705718772869.

A Review on the Sustainability Prospects of Bio Fibre Reinforced Composite Materials

Ashwin Sailesh, K. Palanikumar, N. Mani, and A. Ponshanmugakumar

Abstract A bio composite is a material composed of a matrix (resin) and natural fibre reinforcement. Environmental concerns as well as the exorbitant costs of synthetic fibres sparked the development of natural fibre reinforcement in polymer composite. The concept of using green materials has become more popular over the last decade. With heightened awareness of the importance of environmental preservation, sincere efforts can indeed be cited all over the world in the search for biodegradable and bio-based sources. Bio composites have the proclivity to absorb dampness via the interface, matrix, reinforcement and the zones already adversely impacted by the formation of pores, cracks and delamination of layers. Due to the positive uses of bio fibre materials, many researchers have been obligated to investigate the potential use of natural fibres as reinforcement in bio composites. Due to the mechanical qualities, low density, environmental benefits, renewability, and commercial viability, cellulosic fibres are becoming increasingly tempting for the creation of bio-based products. Natural fibre polymer composites have recently acquired popularity for a variety of industrial applications due to the relatively low density and renewability. The main key factors in the research and development of bio composites are the hazards of synthetic fibres, recycling issues, and toxic by-products. Bio composites are environmentally friendly, renewable, non-abrasive, and non-toxic, with characteristics equivalent to synthetic fibre composites and used in a broad array of applications. Due to the above-mentioned merits, developing nations are increasingly turning to new green materials, including natural fibres, to help meet the demands of weight reduction, environmental concerns, and customer satisfaction. Nevertheless, effectively replacing green bio composites presents multiple barriers. The most daunting

A. Sailesh (✉)
Research Scholar, Department of Mechanical Engineering, Anna University, Chennai, India

K. Palanikumar · A. Ponshanmugakumar
Department of Mechanical Engineering, Sri Sai Ram Institute of Technology, Chennai 600 044, India

N. Mani
Department of Mechanical Engineering, Sri Sairam Engineering College, Chennai 600044, India
e-mail: mani.mech@sairam.edu.in

K. Palanikumar et al. (eds.), *Bio-Fiber Reinforced Composite Materials*,
Composites Science and Technology,
https://doi.org/10.1007/978-981-16-8899-7_20

barrier in this field is the lack of data on the effectiveness of biocomposites characterized by a wide range of constituents. This article outlines the challenges in the development of bio composites towards sustainability.

Keywords Bio fibres · Bio composites · Sustainability · Natural fibre · Biodegradability

1 Introduction

Owing to their eco-friendly and biodegradable nature, bio-composite materials have received considerable attention. There is a greater emphasis on the need to mitigate global warming, ecological disruption and pollution. The research community has been focusing primarily on developing sustainable and eco - friendly materials that could really substitute non-renewable materials that endanger the environment. Bio-composites are opening up new possibilities for addressing current environmental concerns, lowering energy consumption, and lowering carbon residues. Bio-composites are environmentally sustainable, biodegradable, renewable, non-toxic, and possess low density property. These materials are being used in automobiles to curb the weight and improve fuel savings Bio composites are being used in the fabrication of exterior panels in passenger cars. Acoustic properties and crash resistance are improved in parts made of bio-composite materials.

Bio-based materials are made from biological sources such as crop varieties, flora, or other naturally derived resources. They are viable replacement for man-made synthetic fibres [1]. Today's researchers are concentrating their efforts on developing novel materials that have a minimal environmental impact and might be used to replace existing the composites, which cause damage to the environment [2]. Since synthetic products pose major health hazards, natural fibres are the chosen material for the fabrication of sustainable composites [3]. Inclusion of fillers to natural fibres significantly enhances the properties of the material [4].

Demands from various sectors of industries, including the automobile, aircraft, defence, and many others, are becoming more environmentally sensitive. There is an increasing need to produce unique bio-based goods and other creative technologies that can break the world's reliance on fossil fuels [5]. A green economy is a significant potential for improving the health and environmental conditions. A green economy is defined by minimal carbon, and proper utilization of renewable sources of energy [6, 7].

In today's world, manufacturing is centred on sustainable and environment composite materials. The term "sustainable composite material" refers to material composed of a number of various components. Sustainability is an important task in manufacturing, industrial and mechanical engineering. Sustainability is rapidly becoming a worldwide concern, with a strong push for transition. Sustainability leads to reduction of energy and other manufacturing requirement so as to reduce the energy requirement which is the most significant parameter to be considered.

Fig. 1 Green economy

Bio fibre reinforced composites material replaces the costly materials which are not naturally available. The usage of natural fibre reinforced composites leads to environmental protection which saves the mother earth. Now-a-days the fibre reinforced bio polymer composite materials find applications in wide areas especially in automobile sector the bio fibre usage increases day by day.

Sustainable Composites intends to address these issues by advancing the implementation of novel recycling techniques while also developing viable composites made from bio materials such as agricultural wastes, maize, husks, and algae. To satisfy our needs today without jeopardising the resources open for future generations, sustainability necessitates a harmony and forethought of socio economic, and ecological factors. The sustainable natural bio composites pave the way for improvement in manufacturing. Products manufactured from sustainable composites is a major boon for businesses. They boost their revenue because users are conscious of the environmental risks associated with manufacturing processes based on non-green practices. Consumers really need to help the environment, and ecological friendly composite sectors recognises the same. The sustainable composite sector understands that they can use their composite material to strengthen their company's profitability as well.

The current work emphasises a substantial contribution in the field of bio fibre composites. The sustainability of bio fibres has been addressed in detail and finally the future scope of the bio fibre composites is explored in depth.

2 Significance of Bio Fibre Composites

The advent of ecologically friendly and sustainable natural fibre materials which are available abundantly has raised global awareness of environmental challenges [8]. Natural fibre composite materials are made up of natural fibres and polymeric resin that have been bonded together under ideal operating circumstances. A thorough understanding of the characteristics of reinforcing fibre is required [9]. Reinforcement of a natural fibre such as jute, kenaf, cotton, bamboo in a polymeric matrix base is an excellent replacement for the composite material made of man-made synthetic fibres [10]. Natural fibre or the bio fibre composites have improved corrosion resistance, are easier to manufacture, are environmentally benign, and the reinforcing bio fibres needed for the fabrication of natural fibre composites are abundantly available [11].

Natural fibre reinforced composites have the ability to augment the mechanical and physical properties of composites, making them ideal for a wide variety of possible applications. Due to superior fibre starch interactions, composites consisting of starch and cellulose fibres have improved mechanical properties [12]. According to research reports, the production of natural fibre composite material consumes less amount of energy when compared to the energy consumed while fabricating synthetic fibre composite materials. Natural fibres possess the benefit of being compact and lightweight, non-abrasive, non-irritating, non-toxic, disposable, and eco-friendly [13].

Bio fibres have a hollow inner structure arrangement composed of plant proteins. Often these natural fibres possess high mechanical characteristics, however they are relatively low when compared to man-made fibres. Bio fibres exhibits more strength and stiffness. Which are considerable, and they are feasible since they are widely available, affordable, and entirely biodegradable without causing environmental harm. All of these advantageous qualities make bio fibres prominent amongst research groups in order to expand their applicability [14, 15]. Table 1 throws light on the mechanical properties of the some of the important natural fibres. Other significant qualities of natural fibre are shown in Fig. 2.

Table 1 Mechanical Characteristics of potential natural fibres [16–21]

Natural fibre or Bio fibre	Specific Strength	Ultimate Strength in tension (MPa)	Young's Modulus (MPa)
Jute	364.3	393–773	26.5
Coir	494.1	593	04-Jun
Kenaf	185.8	223	15
Hemp	–	389	35
Bamboo	2.63	1.79	12.02
Flax	–	344	27

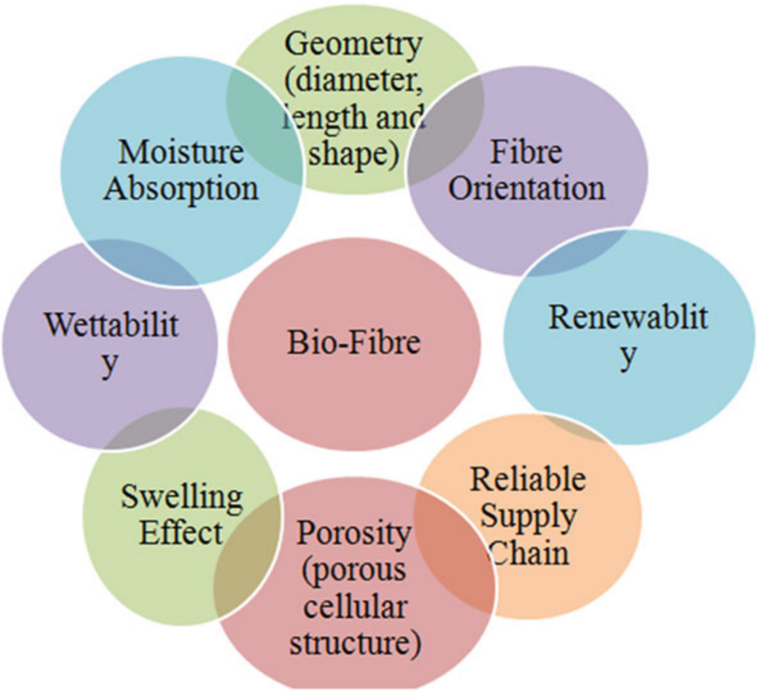


Fig. 2 Significant qualities of bio fibre

3 Application of Bio Fibre Composite Materials

Bio fibre or natural fibre composite materials are used in a variety of applications due to their promising features. The efficiency of natural fibre composites is directly linked to the number of fibres, their length, shape, and organisation of the fibres, as well as their interfacial adhesion with the matrix [22]. An example of a guitar boards manufactured by the use of natural fibre composite material is shown in Fig. 3 and an example of automotive panels is shown in Fig. 4.

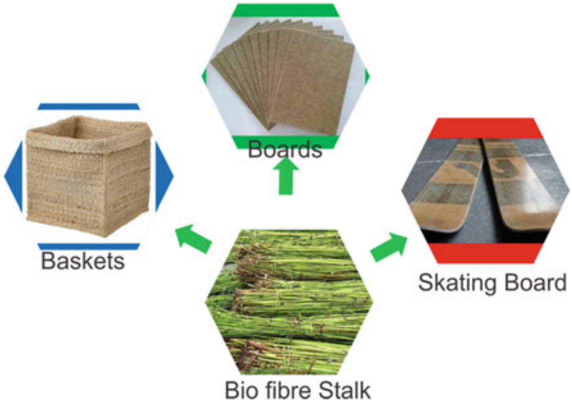


Fig. 3 Application of bio fibre composite materials

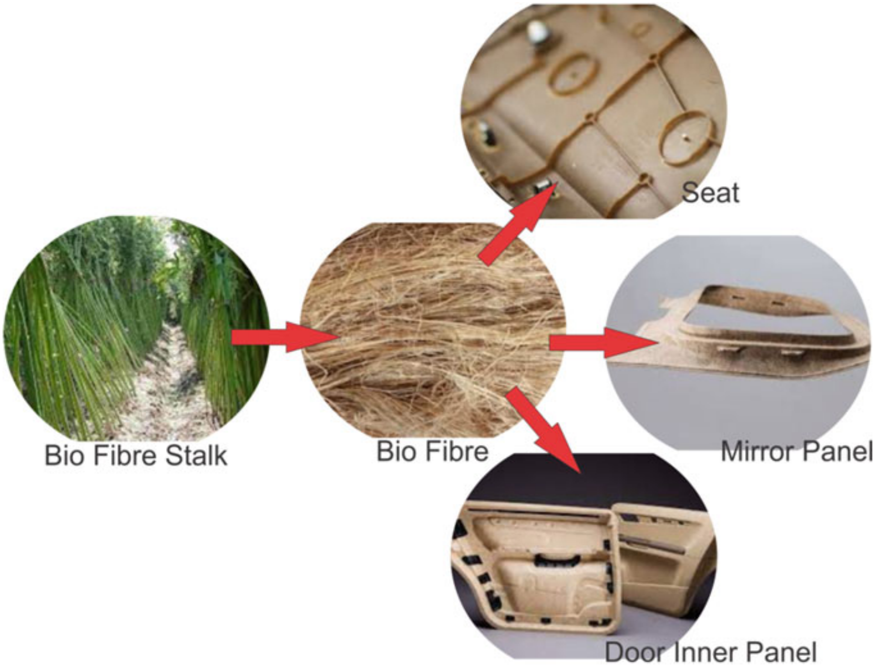


Fig. 4 Application of bio fibre composite materials in automobile sector

The automotive industry is now the most popular use for natural fibre composites. A lot of researchers have contributed to the understanding of the uses of bio composites in automobiles through their diverse studies [23–28]. The light weight of the resulting autos and the simplicity with which materials may be recycled are the most compelling reasons for using natural fibre composites in automobiles [29]. Bio fibres are an excellent reinforcing material for a wide range of automotive components. Door covers, seatback linings, and floor panels, for example, are made of flax, sisal, and hemp [30]. Seat bases, back jackets, and head ties are made of coconut fibres, while automotive parts that need to be soundproofed are made of cotton fibres. The seat backs and car panels are also made of wood fibres and textiles.

By including natural fibres in resin fibre composites the cost of the manufacturing may be reduced. The fabricated natural fibre reinforced composites are also low cost, light in weight, environmental friendly and having zero health implications. As a result, natural fibre composites have a wide range of uses in the home appliance industry. [31].

Natural fibre composite materials play a vital role in energy sector. The usage of natural fibre composites enhances the efficiency of power generation to a greater extent. Bamboo fibre for instance is a potential candidate in the wind power generation. Due to low density of bamboo fibres, it is used in the manufacture of wind turbine blades and the usage of bamboo fibres are appreciated in meeting the raise in the energy demand [32].

The production of materials used for packaging purpose is yet another new application domain for naturally available fibre composites. The bulk resins used in packaging are prepared by using expensive biodegradable polymers. Natural fibres added to degradable resins can lower material costs while enhancing strength, stiffness, and thermal deformation without compromising degradability. As a result, usage of natural fibres in the fabrication of materials in packaging purpose has substantial advantages. Natural fibre composites are currently mostly employed in packaging for disposable items [33]. Banana fibres are being used to make cosmetic boxes and lunch boxes for food packaging. These composites are particularly popular for packing because of their superior mechanical and thermal performance [34].

Due to the sheer excellent sound throughput of natural fibres, they are widely used for percussion instruments. Neck stiffeners and top plates are two examples of lightweight components. They have an advantage because of their substance. Another advantage of natural fibre composite materials is the quick manufacturing time and high sustainability. Flax seed fibres are now commonly employed in the manufacture of speakers [35]. Natural fibre composite materials or the bio fibre reinforced composite materials are used in the manufacture of guitar boards which are conventionally manufactured by using wood. When compared to standard wood boards, the boards produced by using bio fibre composite materials demonstrates better temperature and humidity resistance as well as satisfactory acoustic properties [36].

4 Sustainability of Bio Fibre Reinforced Composite Materials

The pervasive ecological awareness of product quality has resulted in substantial improvements in product design with many eco-friendly items. Amongst the optimistic approaches in addressing the needs is to employ natural fibre reinforced composites and filler materials in polymer composite construction to lessen the reliance on synthetic fibres. The manufacture of bio fibre-based polymer composites has expanded drastically over the years [37]. Composite materials fabricated by using bio fibres as reinforcement are becoming more popular, particularly when compared to synthetic composites [38, 39]. Other pros of using natural fibre or the bio fibre reinforced composites, especially in automotive sectors includes enhanced physical property and thermal stability, enhanced acoustical insulation, and carbon-di-oxide balancing due to the utilization of greenhouse gases during plant cultivation [40].

The automobile sector has undertaken the challenge of application of green composites in order to obtain superior environmental results, reduced energy consumption, and thus the development of cleaner manufacturing techniques and completely reusable materials through the proper disposal stage. The virtue of recyclability also allows the natural fibre compositeto build an ecological marketing approach [41]. Life cycle assessment (LCA) has recently become one of the most prominent approaches for analysing and measuring the environmental effect of commodities, services, over their entire existence. LCA is becoming recognised as one of the most important aspects in sustainable development, particularly in public and corporate decision-making process [42].

A thorough knowledge on the sustainability of natural fibre composite materials or the bio fibre reinforced composite materials is crucial. Sustainability relates to the reliability of the composite materials fabricated by using bio fibres as reinforcing material. With regard to environmental sustainability, green composites or the bio composite materials plays a crucial role. Replacement of hazardous synthetic fibres is the need of the hour and bio fibres are the best candidate for the replacement of the same. Bio fibres can be blended with man-made biodegradable materials to form bio composite materials with improved ecological benefits such as biodegradability, parent material renewability, and reduced greenhouse gas emissions. These are the most important considerations for natural fibre composite materials' long-term viability. Degradation has a number of advantages, including the disposal of hazardous plastic waste and the reduction of waste management expenses because the garbage produced as a by-product is biodegradable in nature. [43].

Increasingly efficient and environmentally suitable composites with improved sustainability encounter obstacles in wide-scale deployment. Plastic and reinforcement sustainability is a complicated process that is governed by factors such as feedstock type, energy input during manufacturing, durability, health effects, and recycling or disposal [44]. For the long-term use of bio fibre composite materials, a uniform protocol for the efficient use of bioresources is necessary. The durability of any bio fibre reinforced composite material intended to replace traditional synthetic composite materials is a vital process. Bio fibre composite applications in Automobile components, infrastructure applications must provide the necessary effective life and superior robustness to accomplish viability. The usage of bioplastics and recyclable materials for sustainable composite applications involves significant scientific obstacles. It is critical to design and construct new classes of bio fibre composite materials that can withstand a wide range of external conditions. The distinction between biodegradable and non-biodegradable composites is equally crucial in terms of applicability [45].

Composite deterioration results from the breakdown of composite materials as well as the loss of mechanical characteristics. The degradation of natural fibre reinforced composites in the external environment is caused by moisture present in the atmosphere, rise in the ambient temperature, and Ultra Violet radiations. The degradation of the fibre is caused by the disintegration of plant proteins. This can degrade the interface between the fibres and the matrix. As a result, the mechanical characteristics of composites are reduced. This is a pivotal point which can affect the sustainability of the natural fibre reinforced composite material [46].

The bonding between the matrix and reinforcement, matrix and alteration of fibre structure due to chemical treatment of bio fibres, hybrid strategy, and desired processing approach are all significant elements in producing efficient bio composites for specific end-use applications. An underlying problem across the broad range of matrix and fibre/filler systems is hybrid synergistic assembly for better compatibility. Since bio fibres are hydrophilic, they have a low compatibility with hydrophobic polymer matrices. This is a serious concern with regard to the sustainability of composite materials fabricated using bio fibres [47].

The disintegration of individual elements in composite materials occurs as a result of the biodegradability of Natural Fibre Reinforced Composite Materials. Biodegradability, recyclability, and sustainability can all have a substantial impact on both the future and current climate. Sustainable and green materials are gaining popularity around the world as a result of the constant increasing of regulations and legislations against dangerous materials [48–52].

Natural Fibre Reinforced Composites are commonly alluded to as sustainable materials because the majority of the materials used in the fabrication are derived from living plants. Industries using natural fibre composite materials for fabrication of products are gaining more profits which indicates a positive sign for the sustainability of composite materials fabricated using natural fibres [53]. The sustainability gains of composite materials over conventional structures in aeroplanes have been demonstrated and examined in several life cycle assessment-based studies. The incineration of natural fibre composites results in excellent carbon credits and a lesser risk to the environment [54].

Sustainability of natural fibre reinforced composite materials can be enhanced by following a suitable hybridization scheme during the fabrication of natural fibre reinforced composite materials. Hybridization is a process of reinforcing two or more fibres in the matrix phase. Interlaminate and Intralaminate hybridization are the two most common types of hybridization. Interlaminate, or overlay, is created by layering layers of different strands. In contrast, intralaminates have the two filaments

Table 2 Hybridization Scheme for optimum sustainability [60–64]

Natural fibre	Synthetic fibre	Benefits yielded
Jute	Glass	Jute fibres were used to provide the best mechanical qualities
Sisal	Glass	By adding sisal fibres, a high tensile strength was attained
Banana	Glass	When combined with glass fibre, banana fibre demonstrated the highest flexural strength. This natural fibre reinforced composite materials have found application in the manufacture if sports equipment
Jute	Carbon	The amount of jute fibre in carbon/jute hybrid composites increases impact and flexural strength

entrapped within a single layer [55]. Hybridization with synthetic fibre laminates can yield natural fibre composite materials with improved moisture retention and worthier mechanical characteristics [56–59]. Table 2 shows the optimized scheme of hybridization for enhancing the sustainability of bio fibre reinforced composite materials.

5 Conclusion

Full degradation of modern materials is essential to lessen the harmful effects of advanced materials on the environment, which is both difficult and time consuming. Researchers should look for materials that are fully incendiary or recyclable for this purpose on a regular basis. Since synthetic fibre-based materials pollute the environment, natural fibre reinforced composite materials are a potential alternative to man-made fibres with a wide range of applications. Some of the significant conclusions can be drawn from the extensive review made is postulated below.

1. Since the green economy is crucial in sustaining an ecologically responsible environment, industries are gravitating towards composite material fabricated by using bio fibres as an alternative to composite materials made of man-made fibres.
2. Recycling is a critical component of trash reduction in order to reduce environmental contamination.
3. Natural fibre composite materials are employed in a variety of industries, including automobiles, aerospace, military, and other biomedical applications, owing to their physical property, cost effectiveness, reusability, and biodegradability.
4. Life cycle assessment is acknowledged as a key environmental management aspect, notably for industry and government decision-making.
5. Life cycle assessment play a crucial role in determining the sustainability and reliability of natural fibre reinforced composite materials.

6. Extensive research on the sustainability implications of natural fibre reinforced composites are required.
7. In the long term, bio fibres will be one of the sustainable and eco- friendly competent, capable of replacing man-made synthetic fibres in a wide range of applications.

6 Future Prospects of Natural Fibre Reinforced Composite Materials

According to the preceding discussion, the usage of natural fibre reinforced composite material in engineering applications is warranted due to their mechanical strength which are in par with the synthetic fibres and reduced ecological consequences. However, regulating and increasing the mechanical characteristics of bio fibre reinforced composite materials presents significant hurdles. Further investigation from the scientific community is also essential to promote and encourage the use of innovative natural fibre as well as novel chemical approaches in the advancement of natural fibre reinforced composite materials. Finally, we may conclude that the development of bio fibre reinforced composite material is rapidly progressing and it is envisioned as a future sustainable material for developing applications.

Further research is required to confront impediments such as dampness in outdoor applications. Thermal stability, humidity, and Ultra Violet radiation, in particular, all have an effect on the service life of natural fibre reinforced composite materials.

References

1. Morão, Ana, and François De Bie. "Life cycle impact assessment of polylactic acid (PLA) produced from sugarcane in Thailand." Journal of Polymers and the Environment, (2019): 2523–2539.
2. Ramesh, M., K. Palanikumar, and K. Hemachandra Reddy. "Plant fibre based bio-composites: Sustainable and renewable green materials." Renewable and Sustainable Energy Reviews, 79 (2017): 558–584.
3. Ramesh, M., et al. "Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: A critical review." Journal of Industrial Textiles, (2020)
4. Das, ParthaPratim, Vijay Chaudhary, and Shubhanshu Mishra. "Emerging Trends in Green Polymer Based Composite Materials: Properties, Fabrication and Applications." Graphene Based Biopolymer Nanocomposites, Springer, Singapore, 2021. 1–24.
5. Mohanty, Amar Kumar, ManjusriMisra, and L. T. Drzal. "Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world." Journal of Polymers and the Environment, (2002): 19–26.
6. Loiseau, Eleonore "Green economy and related concepts: An overview." Journal of cleaner production, 139 (2016): 361–371.
7. https://treelionfoundation.com/en/structure.html
8. Rahman, Pattanathu KSM, and Edward Gakpe. "Production, characterisation and applications of biosurfactants - Review." Biotechnology (2008).

9. Ashwin Sailesh., Palanikumar K. “Mechanical Properties of Flax-Cotton Fibre Reinforced Polymer Composites.” Green Composites Springer, Singapore, (2021), pp 393–411.
10. Saheb, D. Nabi, and Jyoti P. Jog. “Natural fibre polymer composites: a review.“ Advances in Polymer Technology: Journal of the Polymer Processing Institute, (1999): 351–363.
11. Ashwin Sailesh, R. Arunkumar, and S. Saravanan. “Mechanical properties and wear properties of Kenaf–aloe vera–jute fibre reinforced natural fibre composites.“ Materials Today: Proceedings, (2018): 7184–7190.
12. Ashwin Sailesh, and S. Prakash. “Review on recent developments in natural fibre composites” International Journal of Engineering Research & Technology, (2013): 2523–2525.
13. John, Maya Jacob, and Sabu Thomas. “Biofibres and bio composites.“ Carbohydrate polymers, (2008): 343–364.
14. Nair, A. B., and R. Joseph. “Eco-friendly bio-composites using natural rubber (NR) matrices and natural fibre reinforcements.“ Chemistry, manufacture and applications of natural rubber, Woodhead Publishing, (2014), 249–283.
15. Kin-takLau P-y, Min-HaoZhu DavidHui (2018) Properties of natural fibre composites for structural engineering applications. Compos B Eng 136:222–233
16. Fiore V, Di Bella G, Valenza A (2015) The effect of alkaline treatment on mechanical properties of kenaf fibres and their epoxy composites. Compos B Eng 68:14–21
17. Yu Y, Huang X, Yu, Wenji (2014) A novel process to improve yield and mechanical performance of bamboo fibre reinforced composite via mechanical treatments. Compos B Eng 56:48–53
18. Wambua, Paul, Jan Ivens, and IgnaasVerpoest. “Natural fibres: can they replace glass in fibre reinforced plastics?” Composites science and technology, (2003): 1259–1264.
19. Chand, Navin, and Mohammed Fahim, “Tribology of natural fibre polymer composites” Woodhead publishing, 2020.
20. Khan, Mohammad ZR, Sunil K. Srivastava, and M. K. Gupta. “Tensile and flexural properties of natural fibre reinforced polymer composites: A review.“ Journal of Reinforced Plastics and Composites, (2018): 1435–1455.
21. Avérous, Luc, and F. Le Digabel. “Properties of biocomposites based on lignocellulosic fillers.“ Carbohydrate polymers, (2006): 480–493.
22. AL-Oqla, F.M.; Salit, M.S. Material selection of natural fibre composites. Materials Selection for Natural Fibre Composites; Elsevier: Amsterdam, The Netherlands, 2017; pp. 107–168
23. Zhanying Sun, “Progress in the research and applications of natural fibre-reinforced polymer matrix composites”, Science and Engineering of Composite Materials (2017)
24. Rwawiire, Samson, et al. “Development of a bio composite based on green epoxy polymer and natural cellulose fabric (bark cloth) for automotive instrument panel applications.“ Composites Part B: Engineering 81 (2015): 149–157.
25. Al-Oqla, Faris M., and S. M. Sapuan. “Natural fibre reinforced polymer composites in industrial applications: feasibility of date palm fibres for sustainable automotive industry.“ Journal of Cleaner Production 66 (2014): 347–354.
26. Faris M.AL-OqlaS.M.Sapuan, “Natural fibre reinforced polymer composites in industrial applications: feasibility of date palm fibres for sustainable automotive industry”, Journal of Cleaner Production, 66, (2014), 347–354
27. Al-Oqla, Faris M., et al. “Predicting the potential of agro waste fibres for sustainable automotive industry using a decision-making model.“ Computers and Electronics in Agriculture 113 (2015): 116–127.
28. Ali, BA Ahmed, et al. “Implementation of the expert decision system for environmental assessment in composite materials selection for automotive components.“ Journal of Cleaner Production 107 (2015): 557–567.
29. Wilson, Adrian. “Vehicle weight is the key driver for automotive composites.“ Reinforced Plastics (2017): 100–102.
30. Thilagavathi G (2010) Development of natural fibre nonwovens for application as car interiors for noise control. J Ind Text 39(3):267–278
31. Galan-Marin C, Rivera-Gomez C, Garcia-Martinez A (2016) Use of natural-fibre biocomposites in construction versus traditional solutions: Operational and embodied energy assessment. Materials 9(6):465

32. Bajwa DS, Bhattacharjee S (2016) Current progress, trends and challenges in the application of biofibre composites by automotive industry. Journal of Natural Fibres 13(6):660–669
33. Compostable fibre pulp trays, plates and hinged lid containers, www.ckfinc.com/products/earthcycle
34. Nobile D, Alessandro M et al (2012) Food applications of natural antimicrobial compounds. Front Microbiol 3:287
35. YILDIZHAN, Şafak,. "Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications." European Mechanical Science (2018): 83–91.
36. https://blackbirdguitar.com/content/blackbird-el-capitan-acoustic-released-first-made-ekoa
37. ParthaPratim Das, Vijay Chaudhary "Moving towards the era of bio fibre based polymer composites", Cleaner Engineering and Technology, 4 (2021)
38. El-Shekeil YA et al (2014) Influence of fibre content on mechanical, morphological and thermal properties of kenaf fibres reinforced poly (vinyl chloride)/thermoplastic polyurethane poly-blend composites. Mater Des 58:130–135
39. Holbery J, Houston D (2006) Natural-fibre-reinforced polymer composites in automotive applications. Jom 58(11):80–86
40. Brosius D (2006) Natural fibre composites slowly take root. Composites Technology 12(1):32–37
41. Luz, Sandra M., Armando Caldeira-Pires, and Paulo MC Ferrão. "Environmental benefits of substituting talc by sugarcane bagasse fibres as reinforcement in polypropylene composites: Eco design and LCA as strategy for automotive components." Resources, Conservation and Recycling 54.12 (2010): 1135–1144.
42. Saur K, Fava JA, Spatari S (2000) Life cycle engineering case study: automobile fender designs. Environ Prog 19(2):72–82
43. Gunti, Rajesh, A. V. Ratna Prasad, and A. V. S. S. K. S. Gupta. "Mechanical and degradation properties of natural fibre-reinforced PLA composites: Jute, sisal, and elephant grass." Polymer Composites 39.4 (2018): 1125–1136.
44. Álvarez-Chávez, Clara Rosalía, et al. "Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement." Journal of Cleaner Production 23.1 (2012): 47–56.
45. Amar K (2018) Mohanty, SingaraveluVivekanandhan, Jean-Mathieu Pin, ManjusriMisra, "Composites from renewable and sustainable resources: Challenges and innovations." Science 362:536–542
46. de Melo, Renato P., et al. "Degradation studies and mechanical properties of treated curaua fibres and microcrystalline cellulose in composites with polyamide 6." Journal of Composite Materials 51.25 (2017): 3481–3489.
47. Gallos, Antoine, et al. "Lignocellulosic fibres: a critical review of the extrusion process for enhancement of the properties of natural fibre composites." RSC advances 7.55 (2017): 34638–34654.
48. Adeyi, A. J., et al. "Momordica Augustisepala L." Stem Fibre Reinforced Thermoplastic Starch: Mechanical Property Characterization and Fuzzy Logic Artificial Intelligent Modelling. Results Eng 10 (2021): 100222.
49. Zafeiropoulos, N. E., C. A. Baillie, and J. M. Hodgkinson. "Engineering and characterisation of the interface in flax fibre/polypropylene composite materials. The effect of surface treatments on the interface." Composites part A: applied science and manufacturing 33.9 (2002): 1185-1190.
50. Elbadry, Elsayed A., Mohamed S. Aly-Hassan, and Hiroyuki Hamada. "Mechanical properties of natural jute fabric/jute mat fibre reinforced polymer matrix hybrid composites." Advances in Mechanical Engineering 4 (2012)
51. Nayab-Ul-Hossain, A. K. M., Salma Katun Sela, and Sazid Bin Sadeque. "Recycling of dyed fibre waste to minimize resistance and to prepare electro thermal conductive bar." Results in Engineering 3 (2019)
52. Mahmud, Sakil, et al. "Comprehensive review on plant fibre-reinforced polymeric bio composites." Journal of Materials Science (2021): 1–34.

53. Adekomaya, O., et al. “A review on the sustainability of natural fibre in matrix reinforcement–A practical perspective.“ Journal of Reinforced Plastics and Composites 35.1 (2016): 3-7.
54. Mansor M., Salit M., Zainudin E., Aziz N., Ariff H. “Life Cycle Assessment of Natural Fibre Polymer Composites”, Agricultural Biomass Based Potential Materials. Springer,(2015), pp121–141.
55. Almeida Jr, José Humberto Santos, et al. “Hybridization effect on the mechanical properties of curaua/glass fibre composites.“ Composites Part B: Engineering 55 (2013): 492–497.
56. Rubino, Felice, et al. “Marine application of fibre reinforced composites: a review.“ Journal of Marine Science and Engineering (2020)
57. Reis, P. N. B., et al. “Impact response of Kevlar composites with filled epoxy matrix.“ Composite Structures (2012): 3520–3528.
58. Akil, Hazizan Md, et al. “Flexural behaviour of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission.“ Materials Science and Engineering: A (2010): 2942–2950.
59. Flynn, Jeff, Ali Amiri, and Chad Ulven. “Hybridized carbon and flax fibre composites for tailored performance.“ Materials & Design (2016): 21–29.
60. Jothibasu, S., et al. “Investigation on the mechanical behaviour of areca sheath fibres/jute fibres/glass fabrics reinforced hybrid composite for light weight applications.“ Journal of Industrial Textiles (2020): 1036–1060.
61. Sanjay, M. R “The hybrid effect of Jute/Kenaf/E-glass woven fabric epoxy composites for medium load applications: Impact, inter laminar strength, and failure surface characterization.“ Journal of Natural Fibres (2018).
62. Ramesh, M., K. Palanikumar, and K. Hemachandra Reddy. “Comparative evaluation on properties of hybrid glass fibre-sisal/jute reinforced epoxy composites.“ Procedia Engineering 51 (2013): 745–750.
63. Al Rashid, Ans, et al. “Utilization of banana fibre-reinforced hybrid composites in the sports industry.“ Materials (2020)
64. Ali A (2019) Experimental and numerical characterization of mechanical properties of carbon/jute fabric reinforced epoxy hybrid composites.“ Journal of Mechanical Science and Technology, 4217–4226