A Comprehensive Review on Mechanical based and AI based Natural Fibres Reinforced Composite Materials

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ABSTRACT

Nowadays, many people are shifting towards eco friendly materials because synthetic ones cause harm to the environment. Natural fibre based composites like jute, hemp, banana, and sisal are becoming popular since they are cheaper, biodegradable, and easy to produce. These materials are now being used in place of synthetic composites in civil, automotive, and packaging industries. Researchers have tested different combinations of natural fibres and biodegradable plastics to make strong and sustainable materials. This review talks about various types of natural fibres and their properties like strength, moisture resistance, and durability. It also explains how fibre treatment and the use of nanofillers can improve performance of composites. Some studies also show how these composites are being used in civil engineering for structural repair work and with the help of AI methods which have more influence on predicting, optimizing, and improving the mechanical and thermal qualities of composites made from natural fibres. AI can also be used in composite for major improvement in industries of automobiles and different constructions,with the help of AI we can do predictions for production process and maintaining high product quality with more efficiency. These approaches that rely on AI help to create stronger, cheaper, and more eco friendly materials to use in future engineering projects. The main aim of this paper is to highlight the current research on these materials and how they can help in building a greener and improved future.

Keywords: Natural fibre composites, Artificial Intelligence, Mechanical Properties.

1. Introduction

A composite is a material composed of two or more separate materials with distinct properties. Natural fibres are classified as plant based and animal based fibres. The properties of composites based on natural fibres are becoming more widely known to satisfy technical specifications**.** Natural fibre reinforced composites (NFRC) are gaining a wide popularity due to the growing importance of eco friendly environment [1]. They offer a wide range of advantages like durability, strength, chemical resistance, biodegradability, eco friendly nature. Some examples of natural fibres include hemp, bamboo, jute, areca, silk, wood cotton. Researchers are experimenting different techniques to blend these natural fibres in the industry. The orientation of these fibres in the composite is a crucial factor that governs not only the distribution of stress and its capacity to bear load but also the overall properties of the material. These fibres are commonly used in products like clothing, flooring, bags and even in parts of car [2]. Researchers have found out that adding nanofillers enhances the bonding between reinforcing fibres and the matrix, further enhancing their mechanical properties as well. With the growing green environmental policy, it is advised to add natural fibres in biodegradable polymers such as polyvinyl alcohol (PVA). Banana fibre, another type of natural fibre reinforced composite, is a ligno cellulosic fibre with relatively good mechanical properties. It is a byproduct of growing bananas. The main uses of creating such natural fibre based polymer composites are dimensional instability, interfacial bonding, enhanced moisture absorption and moderate strength. The banana plant has leaf sheaths and is a perennial herb that forms pseudo stem [3]. Fibre that has been chemically treated will have its hydroxyl group in cellulose activated that can easily interlock with the polymer matrices. A revolutionary method in the design and production of composite materials is the incorporation of artificial intelligence (AI) technology. AI is employed in the modelling of composite materials using mechanical synthesis, as well as in the prediction of developing the facility to format the models. It improves performance through material selection and design optimisation. To forecast material behaviour, machine learning algorithms examine big datasets. Moreover it improves quality assurance, lowers errors, and increases sustainability. Wood plastic composite (WPC) is further a variety of natural fibre reinforced composites which is made by combining wood with plastic matrix. Conifer, hardwood, and other cellulose-based fibre fillers are the byproducts of the mechanical wood processing industry that are utilised to make the wooden material used in wood plastic composites [4]. Recycled or waste plastic (thermoset, such as phenol plastic, urea formaldehyde, or thermoplastic, such as polypropylene, polyethylene) or polymer materials are utilised in wood-plastic composites. The initial experiments that combined wooden fibres with plastic were held back in 1960 and 1970s. However, at that early technology development were not appropriate to solve the problem given by the fillers, particularly cellulose fibres [5]. During compounding and moulding, it was unable to diffuse through the plastic compositions. Thus, the end products did not possess the advisable physical characteristics. The Fig.1. shows the classification of the natural fibres and

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the aim of this paper is to explore the recent developments and provide a comprehensive study on natural fibre based composites and future directions of it.

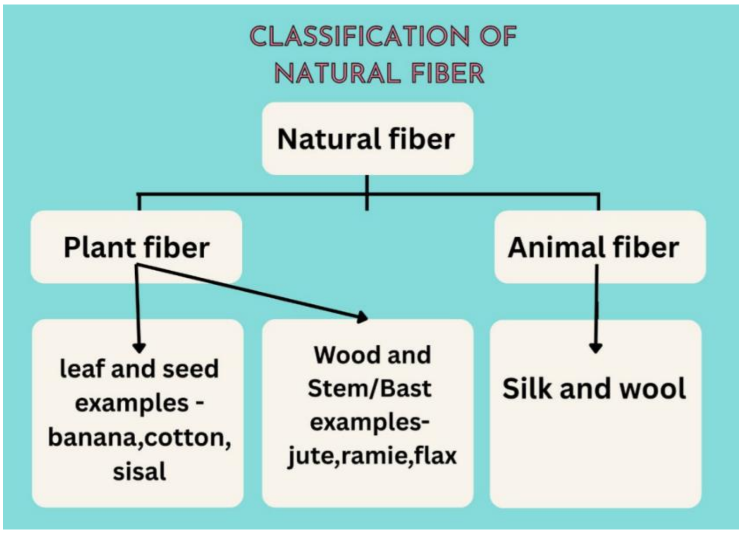

Fig.1. The classification of Natural Fibres

2. Literature Review

Islam et al. [6] experimented hybrid composites consisting of jute and hemp fibres with a polyester matrix demonstrated higher mechanical properties than single fibre composites. Fibre ratio optimization resulted in improved tensile and flexural strength. However, interfacial bonding was limited due to the lack of fibre surface treatment, showing the importance of combining hybridization with fibre modification techniques for further enhanced performance. Tasnim et al. [7] similarly found that addition of nanoclay in a jute/banana fibre composite system using a polyvinyl alcohol (PVA) matrix provided enhanced tensile strength, thermal stability, and decreased water absorption. These results demonstrate that nanofillers are capable of effectively overcoming the weaknesses of natural composites, especially when utilized in conjunction with biodegradable or water soluble matrices. They are increasing their focus on using biodegradable matrices in sustainable composite development employed PVA (an ecofriendly and water soluble polymer) in their jute/banana fibre composites. The addition of nanoclay further enhanced mechanical and moisture resistance properties. While such biodegradable systems still fall behind of synthetic composites in strength, their environmental compatibility makes them suitable for specific applications. Mahboob et al. [8] researched an alternate approach which used integrating natural and recycled fibres into fibre reinforced concrete with recycled aggregates. However, this system does not incorporate a polymer matrix but it did show its future potential for natural fibres as structural applications. This research showed improved toughness and flexural strength, but workability and consistency issues still exist due to the heterogeneous nature of the recycled materials. Shahapurkar et al. [9] study on natural fibre composites mechanical performance and moisture sensitivity are important factors that define their application potential. In their research focusing on Habeshian banana fibre composites, high hardness and interlaminar shear strength (ILSS) were reported, with moderate water absorption. Such results show it’s use in medium performance applications, though in the research only a limited numbers of test parameters were explored. However, more comprehensive performance enhancements were observed in hybrid and nanofiller reinforced systems.

Saha et al. [10] focused on Bambusa tulda fibres treated with sodium hydroxide to create improved bio composites. Their study extended beyond mechanical characterization to include dielectric and dynamic analysis. The alkaline treatment method proved to be effective in removing lignin and hemicellulose which enhanced the fibre matrix interaction, hence improving both the mechanical and electrical properties of the composite. Their approach showed opening possibilities for the use of bamboo based composites in areas such as electromagnetic shielding and structural insulation as alternatives of synthetic composites making it biodegradable. Kavitha et al. [11] looked into how Zea mays root fibres might work as green reinforcements in polymer composites. They studied how potassium permanganate treatment affects the fibres' physical, thermal, and chemical traits. They used high-tech methods like FTIR, SEM, TGA, and p-XRD to check for changes in structure. The observations were supported using both raw and treated fibres in making sustainable bio composites. These days, natural fibre composites are becoming quite common in civil engineering because they are better for the environment and still have good strength. They break down naturally, so they do not create waste like plastic based materials. Corradi et al. [12] checked out how FRCM biocomposites can be used for fixing old brick and stone buildings. Their results showed that these materials are strong enough and also eco-friendly, so they can be used in repair works without much worry. When it comes to using these composites in actual projects, how they behave during drilling also matters a lot. Masannan et al. [13] looked into kenaf/PLA laminates and tested them while drilling. They found that these materials can be drilled without causing too much damage like fibre pullout or cracking. So, it makes them easier to work with onsite, especially in construction or assembly. Additionally, researchers are checking whether these natural fibres are actually strong and can be trusted or not. Kassegn et al. [14] did some experiments on sisal fibres to see how they stretch when pulled, using some camera based method. They noticed that the fibres behaved in a steady way and did not act weird under pressure. This basically means we can use them in real buildings without worrying too much. Natural fibre reinforced polymers (FRPs) are also being used more in real construction work, not just in labs. Albuja-Sánchez et al. [15] studied many real projects where FRPs made from natural sources were used. These materials were not just used for new buildings but also for repairing old ones, which shows they are being accepted better in the field. Recently, combining two or more natural fibres into hybrid composites is being tried out. Felix Sahayaraj et al. [16] mixed jute and hemp in a PLA base and found that the mix worked better than using each one alone. It gave better strength and handled heat well too. So hybrid composites might be the next step forward for using natural materials in civil engineering. Singh et al. [17] examined the multiscale structure of the MXene dispersed hybrid plates by using scanning electron microscopy as shown in Fig2. It was found that the tensile strength of the sisal/glass fibres laminate got enhanced by 42% upon reinforcing MXene. In addition, it was observed that the bending strength and bending modulus of sisal/glass fibres laminate was increased by 34% and 30% respectively, when using MXene nanoparticles were reinforced into the matrix. Based on the experimental results, it was inferred that the surface characteristics of the MXene and CNT nanoparticles play a significant role in improving the tensile and flexural properties of the sisal/fibreglass reinforced hybrid laminate.

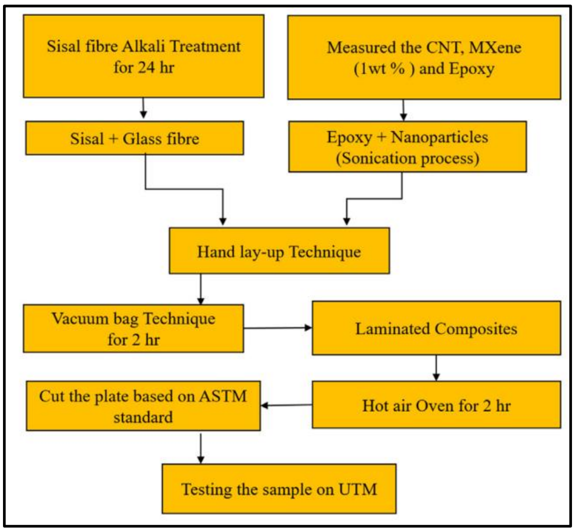

Fig.2. Technique for making natural fibre composite [17]

3. Overview of AI based Composite Material Design Methods

AI methods have caused a revolution in material design for composite materials. They give us new ways to predict how materials behave and to improve their qualities for specific needs. By combining advanced machine learning models with optimization algorithms, scientists and engineers can now design composite materials with custom properties. This helps them improve how these materials work in different uses. One main benefit of AI in material design is that it can predict composite material properties very well. People often use machine learning models like artificial neural networks (ANNs) and support vector machines (SVMs) to predict mechanical, thermal, and electrical properties. These predictions are based on what the material is made of how it's made, and what conditions it is in. These models learn from past data about composite materials. They find complex patterns and connections to make good predictions. ANNs have shown they can predict tensile strength flexural modulus, and fracture toughness of composite materials. This allows engineers to fine-tune material mixes for specific structural needs. SVMs have helped predict thermal conductivity, coefficient of thermal expansion, and dielectric constant of composites. This aids in designing materials to dissipate heat, insulate, and use in electronics. Predictive modelling is not the only tool; optimization algorithms also play a key role in designing composite materials with specific properties. Genetic algorithms, particle swarm optimization (PSO), and simulated annealing are some of the techniques used to optimize material compositions, processing parameters, and structural setups. These algorithms search the solution space over and overlooking for the best mix of variables that meet set goals and limits. For example, genetic algorithms have helped optimize the fibre volume fraction, orientation, and distribution in fibre reinforced composites. This maximizes mechanical strength while keeping weight and cost low. PSO algorithms have also been used to optimize curing cycles and processing conditions in polymer matrix composites. This improves material properties and cuts down production time.

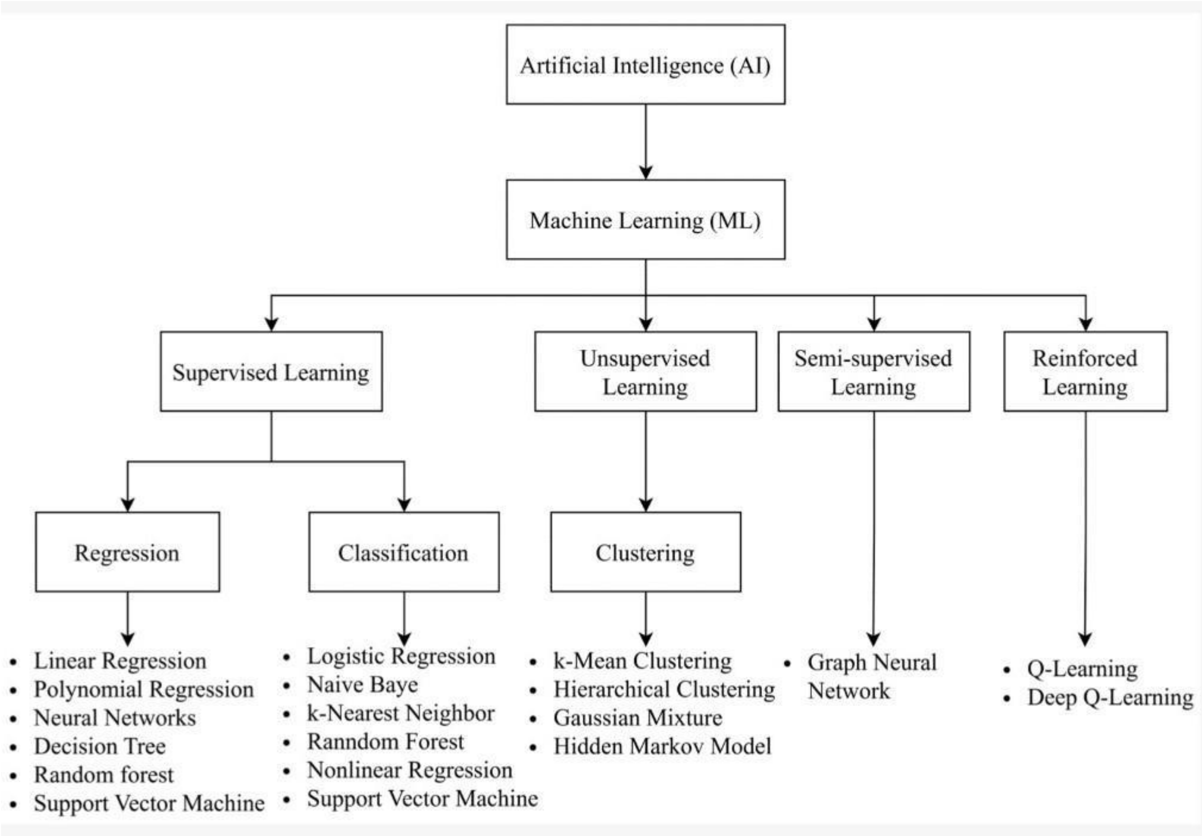

Fig.3. Classification of machine learning algorithms.[18]

AI-driven material design allows for the enhancement of multifunctional properties. This approach leads to the creation of materials with specific combinations of mechanical, thermal, electrical, and optical features. Engineers use multi-objective optimization algorithms to balance conflicting goals and trade-offs. These include the non-dominated sorting genetic algorithm (NSGA-II) and the multi-objective particle swarm optimization (MOPSO). These methods produce Pareto optimal solutions, which show the best trade-offs between different material properties. By looking at the give-and-take between stiffness, strength, conductivity, and other qualities, engineers can create composite materials for specific uses. These might include lightweight structures thermal management systems, and electromagnetic shielding. AI-based material design provides a strong framework to design composite materials with particular properties. It uses advanced machine learning models and optimization algorithms to predict how materials will behave and to improve their properties. Through predictive modeling, optimization algorithms, and real-world testing, researchers and engineers can explore design options, find promising material setups, and speed up innovation in composite materials. As AI methods continue to grow, we expect to see broader and more complex material design abilities. This will lead to further improvements in material performance, sustainability, and functionality.

4. Traditional Methods of Composite and its Variation with AI trained Models

4.1 Predictive Modeling of Mechanical Properties:

Foreseeing the mechanical traits accurately is vital for the performance and structural integrity of composite materials. Yu et al provided insight AI methods like Regression Models and Neural Networks have been used to develop predictive models to forecast the mechanical properties of materials using their composition, processing parameters, and even environmental considerations [19].

4.2 Process Optimization:

When boosting efficiency, reducing costs, or decreasing the number of defects in composite production, optimizing the manufacturing processes is of utmost importance. AI algorithms, including genetic algorithms and reinforcement learning, offer robust optimization frameworks capable of identifying optimal process parameters, tooling configurations, and manufacturing sequences. Studies by both highlight the effectiveness of AI driven process optimization in improving product quality, reducing cycle times, and optimizing resource utilization across diverse manufacturing environments.

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4.3 Defect Detection and Quality Control:

Detecting defects and ensuring quality control are critical aspects of composite manufacturing, where even minor imperfections can compromise performance and safety. Some demonstrates the efficacy of AI driven inspection systems in identifying defects, classifying their severity, and implementing corrective actions to maintain product quality and compliance with industry standards.

5. Conclusion

Composites are meant to have the major properties such as light weight, high strength, high flexularity and very common one, cost efficient. The studies related to the natural fibres like pineapple leaves, bananas, and sisal are discussed so far as being a fibre it gives good mechanical, thermal and environment properties. Whereas many technological and economic challenges need to be addressed before the natural fibre-based epoxy composite can be successfully commercialised. However, uniform nanofibres distribution and hybridization makes it water and moisture resistant which plays a crucial role for it's effective use in almost every sector. Further, more properties are enhancement of mechanical, thermal and water absorption. Blending fibres is a superior way to increase the natural fibre reinforced epoxy's mechanical and thermal resilience. However, the most popular method for creating epoxy composites based on natural fibres, that offer great economy and efficiency is alkaline treatment. AI has a big impact on pushing composite material studies forward. It helps predict how these materials behave under stress and heat with great accuracy. It also makes processes better and spots flaws. By using data models and smart computer programs, AI helps create top-notch, eco-friendly composites. These new materials are custom-made to fit many different engineering needs. These techniques have been widely applied. The technical feasibility, economic viability, and environmental appropriateness of natural fibres filled with epoxy composites make them highly promising for a wide range of engineering applications. It’s future application in aircraft technology and industry will be more extensive. The primary challenges for the near future are to further enhance the mechanical performance and durability of composites while lowering manufacturing costs and creating an environmental friendly approach.

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