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Mechanical and Thermal Behaviour of Natural Fibers as Sustainable Green Materials

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Abstract: Natural lignocellulosic fibers are too much essential for the production of green products and bio-materials. They have various potential capabilities and suitable features from various application points of view. These fibers provide all the necessary kinds of stuff needed for renewable sources worldwide. This research article has been investigated in a systematic way for the thermal, mechanical, and interfacial adhesion characteristics of the fiber polymer generally found in Jharkhand like palm, datura, lemon, and mustard. Experimentation has also been carried out to investigate the Tensile strength, elongation to break, tensile Modulus, and thermogravimetric analysis (TGA). Focus has also been put towards the loss to weight characteristics, water losses and decomposition phenomenon under the action of heating effect. Comparison has been performed for the commonly applicable worldwide fibers and fibers considered in this research article. It has been revealed that fiber materials found in the Jharkhand region are more compromising than fibers used worldwide. Palm fibers have the better characteristics of tensile Strength (160MPa) tensile modulus value (5GPa). Among the various characteristics, the thermal behavior of lemon and datura fibers is best compared to the other. Palm and mustard fibers have stable thermal behavior. It has been observed that percentage mass loss of 18.8% and 24.3% has been noted down at 140^0C and 240^0C, respectively. TGA analysis shows that the considered fibers in this paper are more suitable for the industrial purpose for the application due to their stable thermal behavior. Moreover, palm fibers can be used for the door panels, textiles, packaging and papers, furniture, window framing, electronic uses as insulators, circuit boards, switches, terminals, and dielectrics.

Keywords: lignocellulosic fibers, datura, palm, lemon, mustard, eco-friendly, green materials.

1. Introduction

The quest to reduce dependency on petroleum products has led to the development of new bio-product materials, which can lead to renewable green products and open doors for cleaner production [1]. The governments of various countries have emphasized the usage of bio-based renewable materials due to the constantly increasing price of petroleum products, climate change, and the world's move towards global sustainability [2]. Moreover, the government has realised the importance of available natural resources and proper utilization of them and its waste management in order to sustain in the long run and has led to the development of better schemes, regulations, and promotions for natural bio-based materials, for example, natural fiber composites (NFCs). Natural fiber composites have recently found application and usage in a variety of industries, including furniture, automotive, agriculture, construction, packaging, aerospace, and others, by replacing conventional materials [3].The advantages of being recyclable, abundant, lighter in weight, degradable, lower cost have put NFCs much ahead than their traditional synthetic materials. Moreover, NFCs also enjoy the benefits of being a green product and contribute to the goal of environmental sustainability by being recyclable and degradable in nature. Green products developed using available agricultural waste would pave the way for new renewable materials and be a source of economic growth for a lot of developing nations [4]. Plants (lignocellulosic) are natural fibers that could be used as excellent renewable sources by utilizing them as reinforcement in polymers. To develop new eco-friendly bio-material types [5-7]. These could also be regarded as an excellent choice of reinforcement from both an environmental and an economic standpoint. Sustainability points of view as they are eco-friendly, have less weight, and consume less energy.

Natural fibers can be categorised on the basis of its origin in the plant like leaf, fruit, seed fibers, stem fibers, bast fibers, and skin. Having high specific properties and bearing low cost makes natural fibers in high demand in various industries like furniture, automotive, agriculture, construction, packaging, aerospace, etc. Factors like constituent characteristics, maximum temperature used during manufacturing, degradability, orientation, volume fraction, fiber length and geometry, contribute in General characteristics and characteristics of a product produced from bio-composites. But, when considering the design of green products, the mechanical and chemical properties are the only two criteria considered to a greater extent as there is a co-relation between natural fibers' chemical characteristics and its equivalent mechanical performance [8-9].

Lingocellulosic fibers are nowadays used as the independent and main component of bio-composites. They are being independently used because they have intrinsic procperties that are difficult to change or modified compared to their counterparts, like polymers where properties can be easily modified. This may be why natural fibers have found limiting applications in various fields compared to that of polymers that have been abudantly used in recent years. But, using natural fibers in bio-composites would prove beneficial in providing alternative materials for green solutions [10].

This paper introduces a novel way of investigating the natural fibers available in Jharkhand region of India in particular lignocellulosic fibers, and to test their mechanical and environmental behavior from various technical standpoints. This would ensure creating an ideal database of materials that could prove pivotal in developing green materials that will be eco-friendly and cost-friendly and develop sustainable material of the future with wide industrial applications and open gateways for further research in the bio-materials field.

2. Materials and Methods

From various places in Jharkhand (North-Eastern part of India) [Jharkhand region is abundantly rich in flora and fauna] various wastes of lignocellulosic in abundance have been collected. The physical properties of the polymers which have been considered here are listed below in Table 1.

For the selection purpose of lignocellulosic fibers, analysis of thermogravimetric and characteristics related to their interface were examined.

Table 1: Physical properties of the selected polymers

Polymers	Melt Flow rate at 230^{0}C and 2.2 Kg Load	Yield tensile strength (MPa)	Density (Kg/m^3)
Polypropylene (PP)	12.5 g/10 min	34	906
Low-density polyethylene (LDPE)	0.85 dg/min	11	921
High-density polyethylene (HDPE)	0.7 g/10 min	30	960
Polyvinyl Chloride (PVC)	-	KValue 68	Density- 569 Kg/m^3

2.1. Selection of Fibers

According to evaluation criteria, the preliminary investigation has been performed in a specific way to select the foremost suitable fibers. The choice for the compatibility of the various agricultural waste fiber primary selection was made. This evaluation criterion includes the availability of resources (fibers), cost estimation, reliable properties required to perform the task (mechanical property), renewal period, material density [11-12]. Few species were excluded which did not exhibit the initial criteria for further investigation purpose. *Lemons*, *palms*, *datura stramonium* (hereby will be refereed datura), and *mustard* residues fibers were considered for the outcomes. All the fibers, as mentioned above, were available in considerable quantities in the Jharkhand region. Therefore, they qualify for the physical as well as mechanical properties needed for the demonstration, and were also lower in cost.

Subsequently, qualified samples of fibers were considered for mechanical investigations and thermal behavior to govern their potential capabilities. Samples were made processed and adaptable according to the need for the test to be performed. For example, the specimen to be tested for the tensile test was kept its length 120mm, having an approximate gage length of 50mm. However, depending upon the fiber variations, their diameter has been varied according to the plant species. Therefore, the averaged cross-sectional area calculations are based upon the readings taken for every ten different interpretations of gage length (for every 5mm). All the prepared samples were examined for properties like; tensile strength, Young's Modulus, and elongation gained before the fracture point. According to the standard of ASTM D 3822/01, for every fiber material, five testing trials were performed, and the average value was taken for further investigation. For the tensile test, 3365 Instron (Figure 1) is used, having a 2.0 mm/min crosshead speed.

Moreover, all fibers taken into account originated from considered agricultural waste that were examined in aspects of thermal behavior. It has been reviewed to determine the percentage loss of weight characteristics coming in contact with the combustion and its heating effect. It is concluded that whether these are environment-friendly materials for the production process.

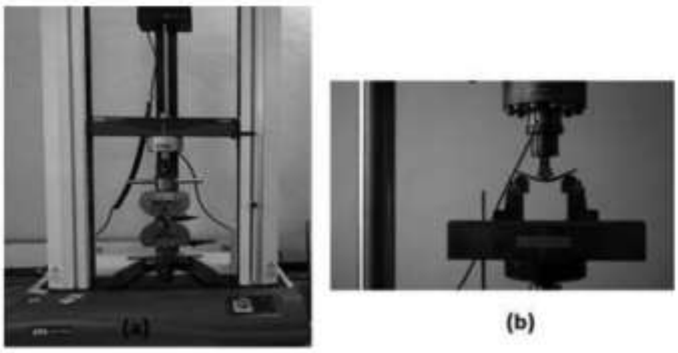

Fig. 1. UTM Instron 3365 (a)Tensile (b)Flexural

2.2 Thermogravimetric Analysis (TGA)

TGA is performed, Monitoring of the changes in physical properties identified and biochemical reactions occurred to fibers when the temperature is allowed to increase at the equivalent rate as it is quite necessary to preserve the information on fibers from agricultural wastes regarding water loss, and decomposition process. TGA experimentation is being performed with the help of an instrument model NETZSCH TG 209/F1 (Figure 2). For an interval of 10ºC/min heating rate in the entire temperature range of 31ºC to 300ºC and 500ºC, thermal Stability was recorded with diverse specimens.

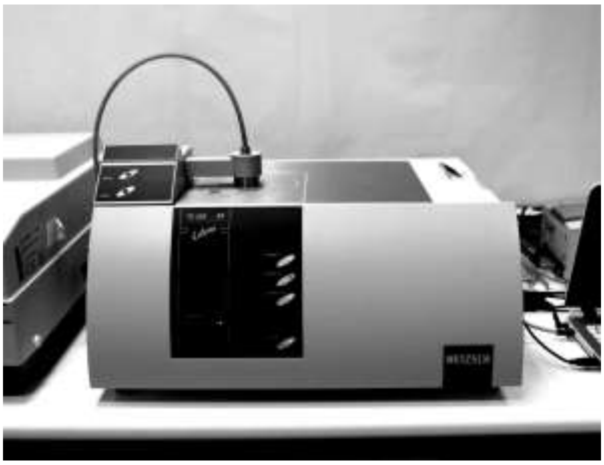

Fig. 2. NETZSCH TG 209/F1

2.3 Interfacial Characteristics

The Pullout technique is an effective technique for examining the interfacial features of different polymer fibers.. Since the features of the interface of fiber-matrix affect the mechanical behavior of the composite materials predominantly. This technique is useful in determining the interfacial effects due to the debonding process and pullout process. The fiber is embedded in the polymer in the pullout experimentation, and the tensile test was done. In this testing procedure, polymer and fiber's free tip both are gripped and pulled apart from those. Fiber has been removed without any breakage from the polymer. This result shows that the interface of fiber/polymer was adhesive failure rather than a cohesive failure of either polymer or fiber. The sustainability and capacity of the polymers or fibers were tested in order to produce environmentally friendly materials.. For this purpose, maximum load capacity, which can sustain the fiber/polymer, is determined with the help of a pullout technique [13].

For the preparation of the pullout samples method of hot mixing, the extrusion process opted. 31 cm of rectangles has been cut for each specimen. The sample is prepared in such a way that each fiber is embedded along the central axis of rectangle. For measuring the length and diameter of the specimen optical microscope is used. The specimen is allowed to act a load of tensile nature with the help of a universal testing machine (Instron 3365). The corresponding load-displacement graph is being recorded, and the speed of the crosshead is kept at 2.0 mm/min.

3. Result and Discussion

In this research article, significant results were observed in finding of different lignocellulosic waste fibers found in the region of Jharkhand. The considerable advantage of using these green bio-based materials in place of using traditional materials results in a waste problem in the environment. In Jharkhand, the wastes from agricultural lignocellulosic are not appropriately valorized nowadays. Properties of this fiber material are not known to industrialists and also about the potential alternative uses of worldwide fibers. These fibers will be useful for the biomaterials for the green products and will also help find such materials that will able to enhance the findings of renewable sources of materials for green products. It will also help increase the GDP of the developing country and industrial markets like India and its neighboring countries.

3.1 Mechanical Investigation

A mechanical investigation has been done to identify the mechanical properties for the agro waste fibers of Jharkhand. The tensile testing test is done for the study of Young's Modulus, elongation in length before the fracture point, maximum tensile strength. All the samples prepared for the investigation have been completed to identify the tensile strength. This investigation has made it possible to know the potential capabilities for the biomaterials [14]. It is compared with the conventional fibers, commonly used in litereature like coir, sisal, flax, hemp, jute, etc. Mechanical behavior (Stress-strain) of lignocellulosic fibers, are shown in figure 3(a)-(d). Figure 4 illustrates the tensile strength property of natural fibers. From the graph, it can be noticed that the palm fiber has the most massive value of tensile strength in the value of 160 MPa due to higher cellulose content in its elements, and of mustard fiber has 60 MPa. The least value is of datura, which is less than 8 MPa. So, it can be summarized that the sequence of the tensile strength in fibers is Palm, Mustard, and Lemon fibers.

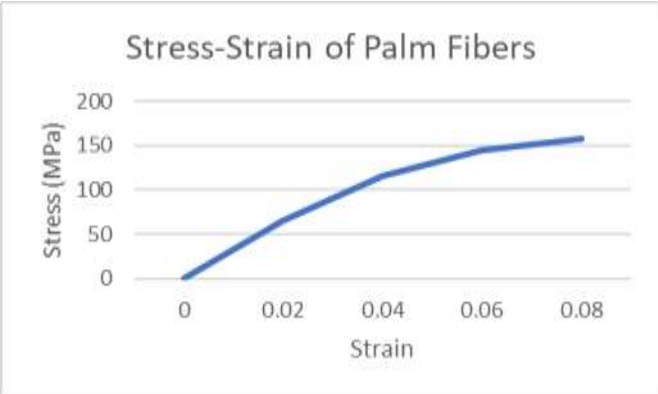

Fig. 3(a). Stress-Strain Diagram of Palm Fibers

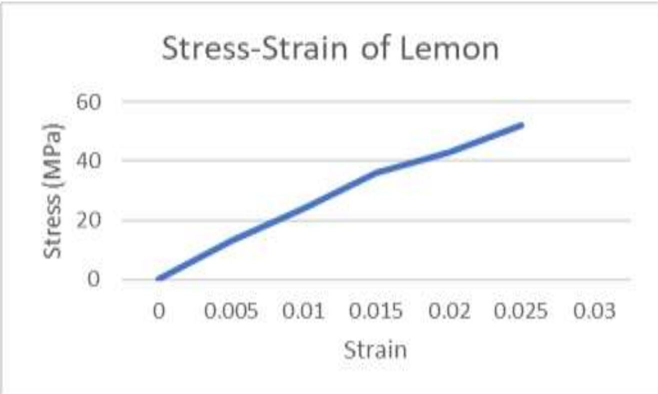

Fig. 3(b). Stress-Strain Diagram of Lemon

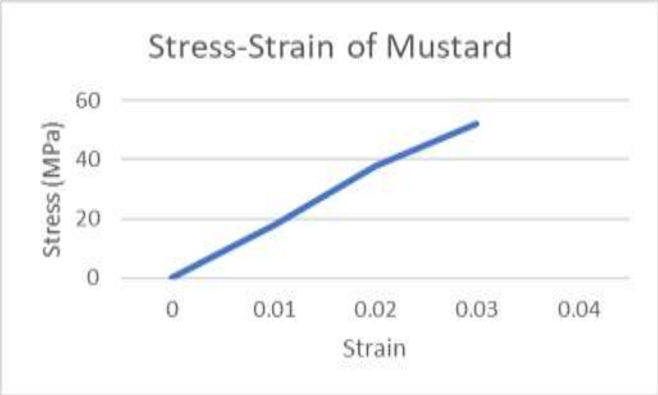

Fig. 3(c). Stress-Strain Diagram of Mustard

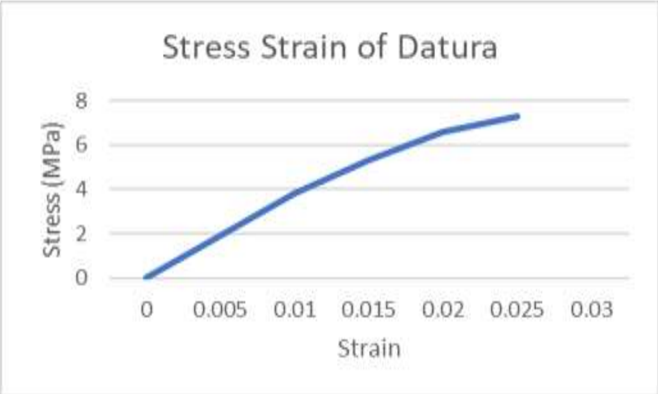

Fig. 3(d). Stress-Strain Diagram of Datura

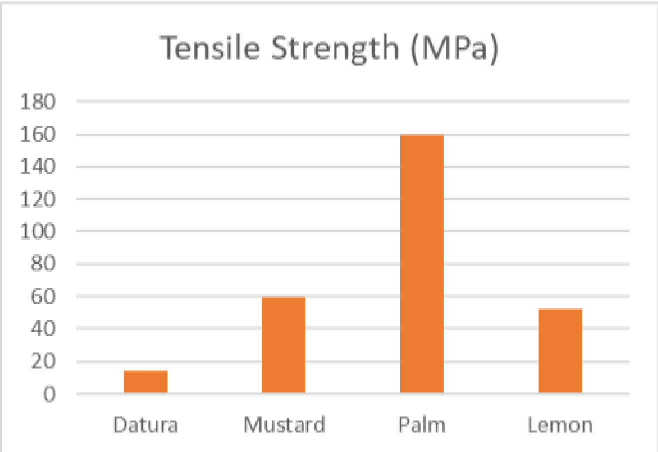

Fig. 4. Tensile strength of fibers compared

Moreover, figure 5 shows the variation of elongation to break the property of the Jharkhand agro-based fibers. It shows that Palm fibers have the maximum value of elongation to break the percentage. They are as follows 0.078%, 0.06%, and 0.,026% of Palm fiber, Mustard, and Datura, respectively. However, the lemon type fiber has the least value of this percentage, i.e., 0.025%. The above observation of elongation to break the percentage value of mechanical properties is very close to each other except the Palm fibers. It results that when one parameter is ignored, it may lead to paying no attention to the other fiber materials if only single criteria are being selected for the selection process. Hence, it concludes that for the selection process of the elements of natural fibers for biomaterial consideration, more than one criterion should be followed.

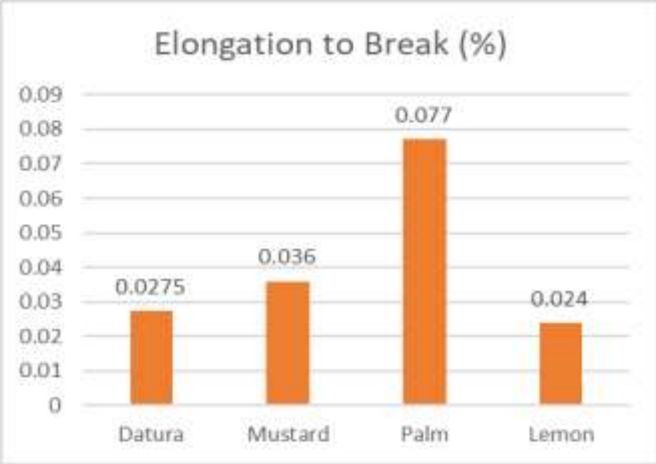

Fig. 5. Elongation to break % of fibers compared

Figure 6 provides Young's modulus criterion having mechanical characteristics for the Jharkhand agro waste fibers. It shows that Palm fibers have a 5.02 Gpa Young's Modulus value, followed by 2.71GPa of lemon. Similarly, the mustard-type fibers have a modulus of elasticity value nearer to 2.35 Gpa, and datura has 0.34 Gpa only. It results that Jharkhand-based fibers have better Young's modulus value promising better natural reinforced polymer composites.

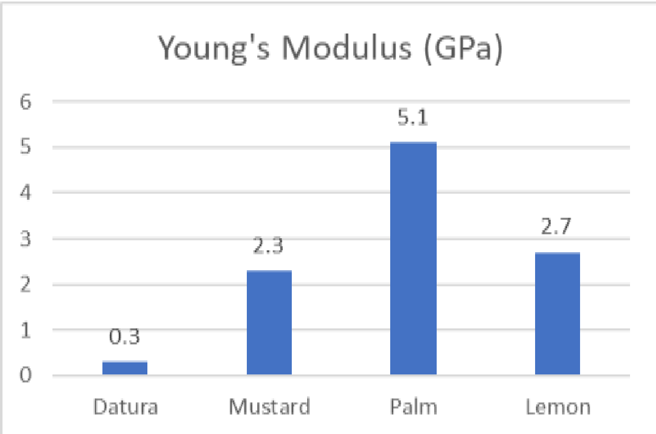

Fig. 6. Young's Modulus % of fibers compared

It is discovered that the inherent capabilities of the commonly used fiber materials and the Jharkhand Lignocellulosic fibers. Comparisons have been made possible with Young's Modulus and tensile strength of the Jharkhand fibers and worldwide fibers. It has been illustrated in Figures 7 and 8. In the table, all the governing mechanical properties of the commonly used fibers are listed out. From figure 7, it can be concluded that Palm fibers have the highest value of tensile strength compared to lemon and mustard fibers.

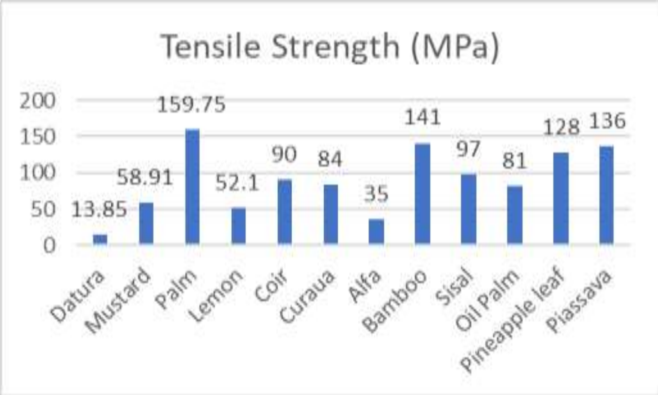

Fig. 7. Tensile strength of fibers compared with other commonly used natural fibers

In figure 8 comparison of the tensile Modulus of the commonly used fibers has been illustrated. It is clear that in contrast with the other fibers, Jharkhand fibers have a better modulus value except for sisal. For example, mustard and lemon type fibers have better Young's Modulus than the Palf, oil palm, and piassava. As a result, the Jharkhand agro-based waste fibers have a more promising capability in biomaterials for industrial application.

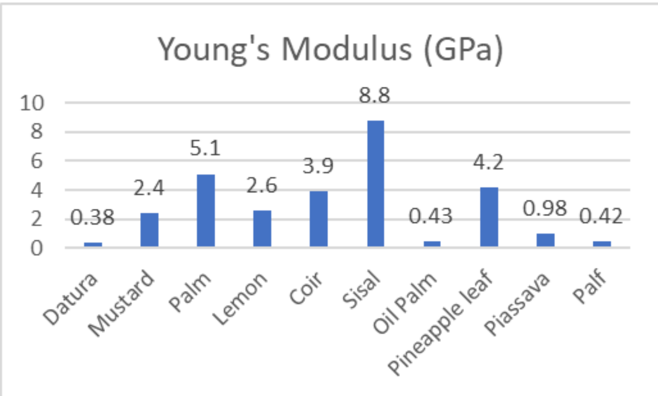

Fig. 8. Young's Modulus of fibers compared with other commonly used natural fibers

3.2 Thermographic analysis (TGA)

All types of fibers considered in literature originated from agricultural waste. Thermal procedures have investigated the effect of the heat on their characteristic's loss of weight percentage before combustion, whether this material is suitable for the further production processes of eco-friendly materials ideal for the environment. TGA testing also has been performed to monitor the physical vicissitudes at the time of increasing the temperature rate consistently. The chemical properties of the fibers also were controlled with the help of this technique. In the decomposition process and for the waste fibers of agriculture, it is quite necessary to find out water losses[15]. In the complete TGA analysis, it has been found that palm, datura, lemon, and mustard are all thermally stable, and behavior towards their losses in mass is minor/negligible.

For an interval of 10ºC/min heating rate in the entire temperature range of 31ºC to 300ºC and 500ºC, thermal Stability was recorded with several specimens and found out that they are stable. With the temperature rise, weight loss was in response to the heat. It was observed that initially, up to 140ºC, the percentage loss in mass is 7.2%. The reason is the evaporation of water as well as the existing lignin content. The moisture content varies depending on the fiber type. The other constituents of fibers, such as hemicellulose and lignin type cellulose, were affected by increasing the temperature above this limit.. In this analysis, it has been observed that there are three stages of the degradation level for lemon fibers. The second level and third level start from the 190ºC to 240ºC and 240ºC to 300ºC. The percentage of degradation at these two levels was 5.17% of the mass and 14.82 % of weight respectively.

Figure 9 shows the complete analysis of the fibers considered in this article. This illustration demonstrates the thermal behavior related to the Stability and degradation of fibers. It has been observed in the experimentation that lemon and datura fibers are more stable for the first temperature range up to 140^0C to 240^0C. Datura and lemon are seen more stable in percentage weight loss at a temperature of 2400C than palm and mustard fibers at a temperature of 140^0C. Except for lemon fibers, all the other considered fiber materials have a weight loss of more than 30%. This stable property of the fiber materials is fitted more suitable for biomaterials related to polymers for an industrial application with a higher thermal stability value.

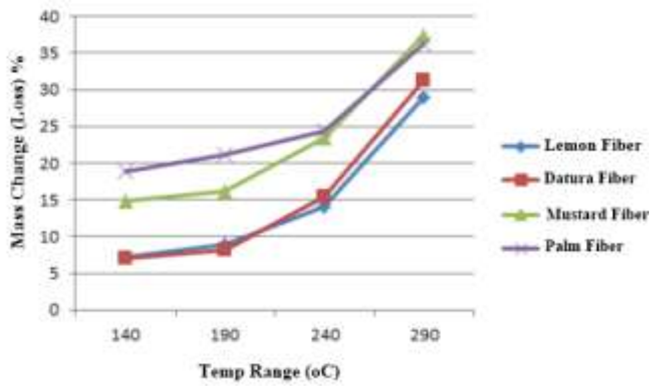

Fig. 9. Thermal Stability of fibers compared

Therefore, it has been theoretically proved from the experimentation that fibers of Jharkhand agro wastes are more suitable for the application in the industries due to their improved mechanical and electrical properties. As an example, insulation in door panels, covering door racks, the framing of windows, railings in households, furniture industry, paper, textiles, insulated electronics, circuit boards, terminals, switches, and dielectrics.

From figure 10, it is revealed that in divergence to percentage mass loss, the Jharkhand fibers prove themselves better than other fiber materials. In comparison to bagasse, banana, bamboo, pineapple leaf and phoenix SP, datura and lemon have been shown to have a smaller weight loss percentage. It shows Jharkhand's higher Stability and improved possibilities for the production of green products.

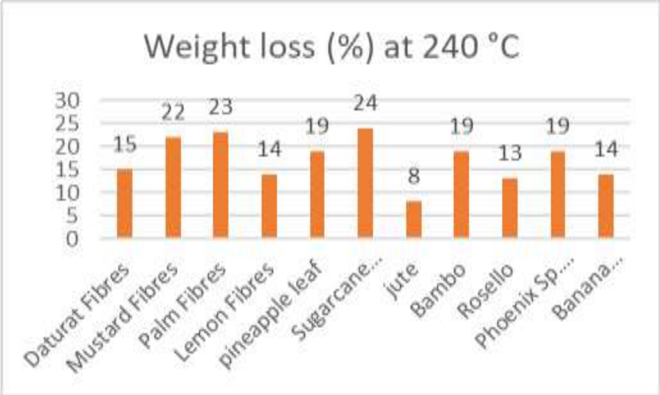

Fig. 10. Weight loss (%) of fibers compared with other commonly used natural fibers

3.3 The pullout test

The pullout technique is one of the vital methods to ensure the compatibility of the lignocellulosic fibers along with various polymers considered in this research article. This method determines the maximum load applied to the fiber up to which it can sustain the load limit by ensuring the interfacial bonding capacity. This method is suitable for indicating the compatible nature of the agricultural waste fibers along with the polymer materials. Preparation of samples for performing the test hot mixing extruding process was opted. Various samples for the testing in the pullout test were purchased and prepared, such as Polypropylene, polyethylene of high density, polyethylene of low density and epoxy [16].

Figure 11 shows the shear strength of the interface of the various polymers. The graph reveals that the interfacial bonding of datura fiber is best, and also of PVC polymer has a shear strength of 5.3 MPa. The reason behind this most significant property of datura is the coarser surface with the other polymers that enable adhesive property. Mustard and Palms have relatively lower interfacial bonding due to smooth surface presence.

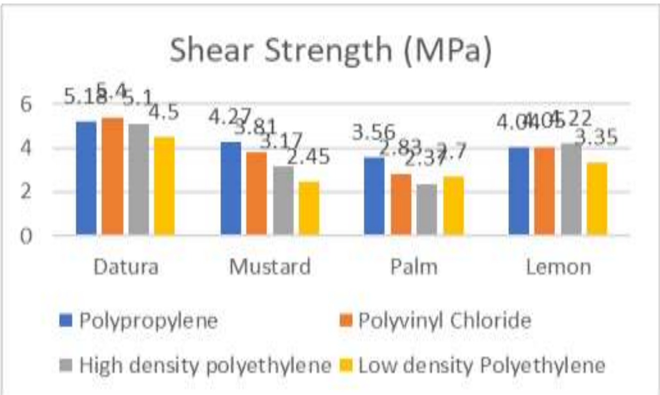

Fig. 11. Shear strength of fibers compared through use as Polymers

Conclusion

In this research article, Jharkhand lignocellulosic fibers' interfacial characteristics are performed successfully. The thermal and mechanical properties of the Jharkhand fibers are also have been investigated by performing the experiments. A comparative analysis has been done to investigate the inherent capabilities and suitability of worldwide fibers and Jharkhand fibers. It has been concluded that the Jharkhand lignocellulosic are more suitable due to their increased mechanical strength, thermally stable, and good adhesive forces in the interfaces. It has also been observed that the fibers of Jharkhand's are more compatible with different types of polymers for biomaterials applications. It can be concluded that Palm type fiber materials have better mechanical strength, followed by elongation to break and tensile strength compared with that of mustard fibers. Thermal Stability of the said fibers is found to be better in the case of lemon fibers, and datura fibers due to their mass to loss percentage are best at 240^0C and 290^0C.

Compared to pineapple leaf, bamboo, roselle, bagasse, and phoenix SP, lemon and datura fibers are most suitable for thermal characteristics, as they have less weight ratio at 240^0C. Additionally, after the detailed analysis of fiber materials, it can be suggested that extensive production of these green products can be enhanced for growing countries due to their low cost and being eco-friendly to the environment. Furthermore, the enhanced interfacial bondings of the Jharkhand fibers brings new opportunities for sustainable industries producing green products. It has been observed in this paper that PVC fibers and datura fibers are the best fibers regarding the shear stresses with all types of polymers. The Jharkhand waste agro fibers' industrial applications are found suitable for door panels, textiles, packaging and papers, furniture, window framing, electronic uses as insulators, circuit boards, switches, terminals, and dielectrics.

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Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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