

## The Improvement of Modified Rice Straw Fiber/Polyvinyl Alcohol Thermoplastic Polymer Composite Using Cold Plasma Technology

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**Abstract:** The use of natural rice straw as a filler for composite materials has not been optimally utilized; only around 7–16% of the grain is used in the industry. Various developments have been carried out, including its use as a filler or reinforcement for wood polymer composite products, but it is not effective because of poor interfacial adhesion. An alternative to increase the effectiveness of straw fibers in wood composites is by using cold plasma (atmospheric) treatment. In this research, composites consisting of straw fiber and biodegradable polyvinyl alcohol (PVA) matrix were made with and without cold plasma injection treatment. PVA is used because of its hydrophilic nature and function as a matrix. This research aims to determine the effect of cold plasma injection on straw fiber/PVA composites. The method used consists of preparation of straw fiber and composites, flexural testing with time variations of 10, 20, and 30 sec, morphological analysis using SEM to determine surface roughness, and FTIR test. The results showed that treatment with and without plasma provided significant differences in roughness. Plasma causes roughness to increase, thereby increasing the adhesion of the interface to the matrix.

**Keywords:** flexural; matrix; polyvinyl alcohol; roughness; surface adhesion

### ■ INTRODUCTION

Rice straw as an agricultural by-product has not been properly processed in Indonesia. Rice straw is a part of the rice plant that has been removed from its contents so that only the stems and leaves remain. The amount of rice straw is very large because Indonesia is one of the major rice producers on the Asian continent [1]. If calculated from the dry mass of rice, the ratio of the mass of rice straw and its contents is 1.4. So, every rice harvest will get 1 to 1.5 kg of rice straw. The total rice production in Indonesia reaches an average of 70 million tons of milled dry grain, so the potential rice straw waste generated can reach 103.57 tons per year [1-2]. So far, most of the rice straw is not processed further and is only collected for composting or burned by farmers, thus potentially causing waste accumulation and environmental pollution in the form of greenhouse gas emissions (CO<sub>2</sub>,

N<sub>2</sub>O, CH<sub>4</sub>) or air pollution (dust, SO<sub>2</sub>, etc.) [3-5]. Efforts or processing technologies are needed to reduce the amount of rice straw waste with steps that can increase its economic value without polluting the environment.

The exploration of innovative solutions for processing rice straw waste holds tremendous potential, with one promising avenue being the creation of composite materials [6]. Table 1 illustrates a juxtaposition of the cellulose, hemicellulose, and lignin content in rice straw in comparison with other materials. From Table 1, rice straw has a higher cellulose, hemicellulose, and lignin content compared to other materials that are popularly used as natural composite, namely water hyacinth and corn stover. Rice straw, classified as a natural fiber, boasts a composition comprising cellulose (40–50%), hemicellulose (20–40%), and lignin. Cellulose acts as the structural backbone of

**Table 1.** Composite constituent contents of various natural materials

| Source         | Cellulose (%) | Hemicellulose (%) | Lignin (%) | Reference |
|----------------|---------------|-------------------|------------|-----------|
| Rice straw     | 35–50         | 20–35             | 10–25      | [7]       |
| Water hyacinth | 18–31         | 18–43             | 7–26       | [7]       |
| Corn stover    | 40–45         | 25–35             | 7–10       | [8]       |

the straw, while lignin serves as its protective layer. These two vital components form a robust lignin-carbohydrate complex structure through covalent bonds (anisole bonds) and noncovalent bonds (hydrogen bonds). This intricate interplay among cellulose, hemicellulose, and lignin culminates in the formation of a lignocellulosic matrix, endowing the composite with commendable properties.

Composite comes from the verb "to compose" which means to arrange or merge. Composite means a combination of two or more different materials. Composite is a series of two or more materials combined into one microscopic material where the constituent materials still look like the original and have working relationships that are capable of displaying desired qualities. Another definition of composite is a multi-phase system of properties with a combination, a combination between matrix or binder material with amplifier [9-10]. Given rice straw's rich cellulose and lignin content, it holds significant potential for applications spanning wood, fiber, and various other materials. However, despite these promising prospects, rice straw-based composites encounter challenges, particularly in their application, where they often exhibit poor compatibility with adhesives, leading to suboptimal mechanical strength [11]. In automotive and construction industries, where the mechanical strength of composites is paramount, intervention in the composite manufacturing process becomes imperative. Addressing this challenge involves enhancing compatibility with polyvinyl alcohol (PVA) blends to elevate mechanical capabilities, a goal that can be achieved through rigorous flexural analysis. The matrix used in this research is PVA, which is a synthetic polymer with biodegradable and hydrophilic properties. PVA is usually used for packaging because of its elastic properties when formed into a film. Previous research related to the synthesis of thermoplastic polymers using PVA with natural fiber fillers, including

using castor bean shell fiber, ginger dregs, and palm shell fiber, shows that the addition of cellulose fiber can improve mechanical properties, make the composite resistant to heat and reduce water vapor absorption. However, uneven fiber distribution results in decreased tensile properties and lack of adhesion bonds [9]. So, the latest in this research is an alternative plasma jet technology that improves the mechanical properties and adhesion bonds of the PVA and rice straw fiber.

Plasma is an area where electron collisions occur, formed because there is sufficient energy for electron ionization. An alternative technology that holds promise for modifying the surface of straw fibers is the use of cold plasma. Cold plasma occurs at low temperatures and pressures. Cold plasma has the limitation of non-continuous process properties, and a vacuum system has high operational costs even though it has good repeatability at low pressure. In this research, this problem can be overcome by carrying out treatment at atmospheric pressure. Preliminary research related to the development of cold plasma at atmospheric pressure using dielectric barrier discharge, microwave discharge and radio frequency glow discharge techniques has been carried out although references for the development of cold plasma still need to be improved, so this research is important to carry out for the use of plasma [3]. Cold plasma treatment offers several advantages, notably the absence of harmful liquids or gases, rendering it environmentally safe. Additionally, cold plasma treatment enhances composite surface adhesion without compromising the internal properties of the material. This study, therefore, sets out to comprehensively analyze the impact of cold plasma treatment time on the flexural strength of the composite interface. By delving into the intricacies of plasma technology, this research aims to contribute valuable insights into an environmentally friendly and effective approach for

enhancing the mechanical performance of rice straw-based composites [10].

In essence, this study bridges the gap between the potential of rice straw waste and its effective utilization through composite material creation. Through meticulous exploration of composite properties, compatibility challenges, and the innovative application of plasma technology, this research endeavors to pave the way for sustainable and resource-efficient solutions in diverse industries, aligning with the imperatives of environmental conservation and responsible material utilization.

## ■ EXPERIMENTAL SECTION

### Materials

Rice straw, which is used from harvests by farmer groups in Central Java, Indonesia, is in the form of stems of the "gogo" variety of rice straw. This variety has hard straw stems and a 3–4 months harvest age, so its availability is maintained. Pure argon gas with a purity of 99.99% and UHP grade, PVA Merck 1.14266.0100, and aquadest were used in this experiment.

### Instrumentation

The electrical power source in plasma jet applications comes from a high voltage inverter 1000 kv/High Voltage Power Supply (HVPS). Plasma jet manufactured with Sony VTC 6 Battery 18650, Modul BMS 2S 20A, aluminum foil, acrylic sheet, spot welder, adjustable DC power supply DEKKO PS3010L+, banana socket black female, banana socket red female, banana jack male, step up down adjustable AC voltage regulator 3000 Watt 0V–250V AC, 3pcs/lot UCC27425P UCC27425 27425 DIP-8. HVPS is connected to an aluminum electrode and stainless-steel electrode. Flexurat test properties used strength ZP Recorder 50N Imada. Morphological assessment composite test used scanning electron microscopy (SEM). The FTIR analysis was conducted using state-of-the-art equipment from the renowned brand Shimadzu.

### Procedure

#### **Composite preparation**

The initial step in the process involves isolating rice straw from manure and subjecting it to a thorough

cleansing with clean water. Subsequently, the washed straw undergoes a natural drying process in the sun. Post-drying, the straw is meticulously chopped into smaller dimensions and sieved to achieve a uniform size of 1 mm. Each glass composite mold, measuring  $7.5 \times 7.5 \text{ cm}^2$ , is then allocated a specific weight of straw fiber, precisely calibrated at 3.5 g. Maintaining a balanced composition, the straw fiber to PVA ratio is meticulously set at 20:80 wt.%. Distilled water is utilized as a key component in the formulation of the PVA matrix. Silicone oil is introduced to streamline the removal process and ensure the integrity of the final composite. This strategic addition facilitates the seamless detachment of the composite from the mold. The careful consideration of these procedural steps ensures not only the quality of the composite but also an efficient and controlled manufacturing process, adhering to established standards and best practices.

The composite is crafted from a blend of straw fiber and a PVA matrix, exhibiting a composition ratio of 20:80 (wt.%), respectively, and featuring fiber lengths of 1 mm. The fabrication process involves the meticulous preparation of the polyvinyl alcohol matrix by blending PVA powder with distilled water in a ratio of 1:8. The mixture is stirred and heated using an electric heater within the temperature range of 78–100 °C until complete dissolution is achieved. Following this, straw fiber pieces, subjected to plasma treatment for varying durations (10, 20, and 30 sec), are stirred in a glass beaker until uniformly distributed. The resultant mixture is then poured onto a glass mold that has been previously coated with silicone oil. The composite blend undergoes a drying process in an oven set at temperatures between 58.5–66.0 °C, ensuring solidification over 60 min. Subsequently, the composite is left to stand at room temperature for 8 h, facilitating the drying process. This step is crucial to prevent excessive hardening of the composite within the mold, ensuring ease of removal. Upon completion of the drying period, the composite is carefully removed from the mold and subjected to a reheating process in the oven at temperatures ranging from 58.5–66.0 °C for an additional 60 min. This reheating step further enhances

the composite's rigidity, contributing to its overall structural integrity and mechanical performance. The meticulous crafting process outlined here underscores the importance of precise control over each step to successfully synthesize a durable and rigid straw fiber-PVA composite.

### Experimental design jet plasma

The cold plasma employed in this study utilizes a HVPS. The use of HVPS provides a distinct advantage in that the ionization process occurs in a non-equilibrium state, resulting in the production of low-temperature plasma ranging from 58.5 to 66.0 °C [12]. The HVPS is intricately connected to a stainless-steel rod-shaped electrode, enclosed within a glass tube to implement this. Meanwhile, an aluminum tape is connected to the ground at the bottom. The argon gas is then circulated through the glass tube at a velocity of 0.2 L/min. For a visual representation, the circuit of the cold plasma device is illustrated in Fig. 1. This innovative configuration allows for precise control over the ionization process, ensuring that the produced plasma maintains a relatively low temperature. The stainless-steel rod-shaped electrode, enveloped by the glass tube, forms a critical component of the system. Simultaneously, the grounding through the aluminum tape adds another layer of stability to the setup. Moreover, the flow of argon gas through the glass tube at a specified speed contributes to the overall efficiency of the cold plasma generation process. By incorporating HVPS and carefully orchestrating the components, this

cold plasma system is tailored to operate optimally, offering a controlled and effective means of generating plasma for experimental purposes [13]. As depicted in the circuit diagram in Fig. 1, the integration of these elements highlights the systematic approach employed in creating a reliable and precisely controlled cold plasma environment for the study at hand.

### Morphology test

In the methodology section of our paper on composite synthesis using rice straw, the morphological evaluation of the composite material, both before and after plasma treatment, was conducted through SEM. Unlike traditional light-based microscopy, SEM utilizes electron scattering for a more detailed analysis. The process involves capturing electrons by the detector, allowing for the generation of high-resolution 3D images. SEM is a valuable tool for understanding fracture mechanisms and material behavior under significant loads. To explore the structural changes induced by plasma treatment, SEM played a crucial role in providing detailed insights into the composite's morphology [14]. The microscopic examination was instrumental in deciphering alterations at both the surface and internal structure levels. By leveraging SEM, we gained a nuanced understanding of the topographical modifications resulting from plasma treatment, shedding light on interfacial characteristics and contributing essential data for optimizing the synthesis process [15].

In the context of our research methodology, SEM serves as a cornerstone for the morphological assessment, allowing us to visualize and interpret the effects of plasma treatment on the composite material. The high-resolution 3D images obtained contribute to our ability to draw meaningful conclusions about the transformative impact of plasma treatment on the structural and mechanical properties of the analyzed composite. This meticulous approach using SEM aligns with our commitment to robust scientific methodology, ensuring the integrity and credibility of our findings in the realm of composite material synthesis.

### Flexural test

The assessment of flexural properties was meticulously conducted using Imada's Strength ZP

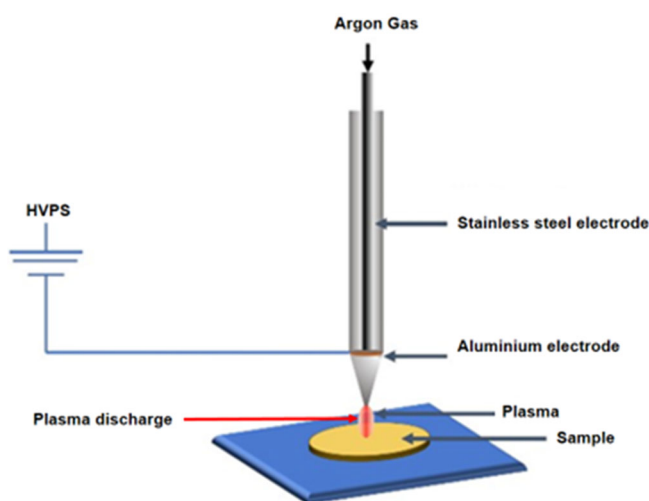


Fig 1. Cold plasma system illustration

Recorder 50N, adhering strictly to the established ASTM D790 testing standards [16]. To ensure precision in the evaluation, the composite under examination was carefully cut to meet the ASTM-prescribed dimensions of 0.5 inches in width and 2 inches in length. The flexural test measurements followed the well-recognized ASTM D790 standard three-point bending test method. In this method, the specimen is subjected to transverse testing, with a vertical load applied using a constant force. The material specimen is strategically positioned atop two support points, and a load is precisely administered at the center point [17].

This systematic approach to flexural testing is instrumental in comprehensively understanding the composite's structural behavior under load. The adherence to standardized testing protocols ensures the reliability and reproducibility of the obtained results, allowing for meaningful comparisons and analyses. The utilization of Imada's Strength ZP Recorder 50N adds an extra layer of precision to the testing process, further enhancing the accuracy of the flexural property assessments. Such meticulous testing methodologies are imperative in gauging the material's performance characteristics and formulating informed insights into its mechanical response under varying conditions.

In the flexural test process, the force applied to the specimen will deform the material and cause stress. The material deformation process produces data related to flexural strength (1) and maximum strain (2) [18].

$$\sigma_{fm} = \frac{3.F_m.L}{2.b.d^2} \quad (1)$$

Based on Eq. (1),  $\sigma_{fm}$  represents the maximum flexural stress in  $N/mm^2$ ,  $F_m$  is the maximum force applied in N,  $L$  denotes the distance between the two supports (converted to millimeters as 1 inch = 25.4 mm),  $b$  is the width of the sample measured at the center in millimeters, and  $d$  is the thickness of the sample measured at the center in millimeters. The concept of maximum stress is crucial in understanding material behavior during the flexural test. It specifically refers to the stress experienced by the material when it reaches the point of fracture or failure in the course of the flexural test. In this test, the material undergoes loading until it eventually fractures. At the

fracture point, the material undergoes the maximum stress, representing the point of failure. This approach allows for a detailed examination of the material's ability to withstand bending forces and provides insights into its structural integrity. By employing the ASTM D790 standard and calculating the maximum flexural stress, we gain valuable information about the material's performance under load and its susceptibility to fracture, contributing to a comprehensive understanding of its mechanical characteristics was calculated with Eq. (2) [19];

$$\epsilon_f = \frac{6.D.d}{L^2} \quad (2)$$

where  $\epsilon_f$  is the maximum strain,  $D$  is the maximum deflection,  $L$  is the support length (mm), and  $d$  is the composite width (mm).

#### **FTIR spectroscopy test**

In the investigation of composite synthesis using rice straw, a crucial aspect of our methodology involved employing FTIR analysis to examine the functional groups present in the fibers before and after plasma treatment. This analytical approach allowed us to gain valuable insights into the chemical changes occurring at the molecular level, shedding light on the impact of the plasma treatment on the composition of the rice straw fibers. Before delving into the specifics of the FTIR analysis, it is essential to emphasize the significance of this technique in elucidating alterations in functional groups. By scrutinizing the FTIR spectra, we were able to discern any shifts or modifications in characteristic peaks associated with chemical bonds within the rice straw fibers. This comprehensive examination enabled a detailed understanding of the molecular changes induced by the plasma treatment [20].

The FTIR analysis was conducted using state-of-the-art equipment from the renowned brand Shimadzu, specifically the Shimadzu Prestige model. This choice of equipment was deliberate, as Shimadzu is recognized for its precision and reliability in delivering accurate spectroscopic data. The selection of Shimadzu Prestige for our FTIR analysis was based on its reputation for excellence in spectroscopic instrumentation. The instrument's advanced capabilities played a pivotal role

in ensuring the accuracy and reliability of our results. This meticulous choice of equipment underscores our commitment to employing cutting-edge technology to enhance the precision and credibility of our experimental approach [21].

## ■ RESULTS AND DISCUSSION

### Morphology Test Using SEM

The results of SEM testing on 4 samples can be seen in Fig. 2(a-d). Fig. 2(a-c) provides a comprehensive visual representation, showcasing the distinct surface characteristics of straw fibers subjected to varying durations of plasma treatment, specifically at 10, 20, and 30 sec. The observed changes in surface roughness are intricately tied to the etching process initiated during plasma treatment. As the plasma interacts with the fiber surface, it induces alterations in the fiber's contours. The consequential heat generated in this process contributes to the degradation of polymer bonds on the surface of the lignin, resulting in a visually distinctive peeled-off appearance. This transformation in surface roughness is not merely a visual alteration; it plays a pivotal role in

augmenting the overall strength of the composite. The rougher surface created through plasma treatment fosters a more robust interaction with the PVA matrix, enhancing the adhesive bond between the two materials. The structural changes observed in Fig. 2(d), where no plasma treatment is applied, reveal a smoother and more uniform surface of the fiber.

Fig. 2(a-c), on the other hand, depict intriguing details such as blisters, hills, gaps, and a porous appearance along the fiber surface. These features directly result from the strong interaction between the reactive species, electrons, and ions formed in the plasma with the straw fiber surface. The pronounced surface roughness facilitates a tighter bonding of the PVA matrix, creating a composite material with improved mechanical properties. Furthermore, the alterations in the properties of PVA, transitioning from hydrophobic to hydrophilic characteristics [22], are noteworthy. The positive ions, electrons, and reactive species within the plasma bombard the PVA surface rendering it receptive to plasma radiation and reactive in nature.

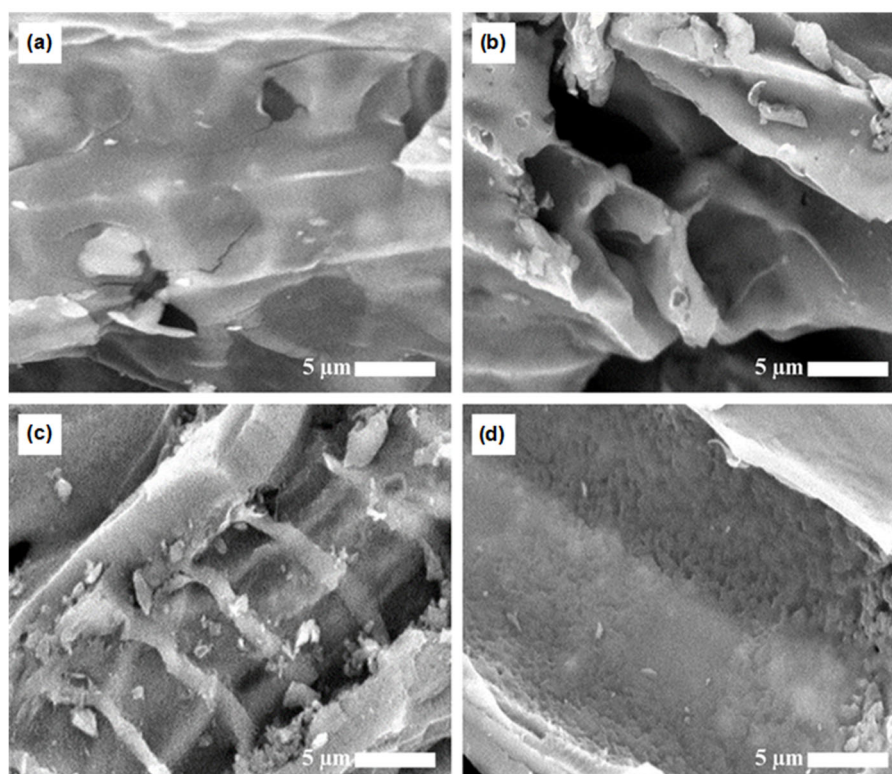


Fig 2. Straw fiber with plasma treatment (a) 10, (b) 20, (c) 30 sec and (d) without plasma treatment

Morphological changes in PVA, involving degradation reactions and the formation of polymer molecules [23], are crucial factors contributing to the observed blisters on the surface. These molecular species tend to escape the PVA matrix, becoming trapped in gas bubbles, and forming distinct blisters. Additionally, the creation of amorphous regions within the crystalline structure of PVA, induced by its interaction with plasma [24], adds another layer of complexity to the observed morphological changes. The collision of reactive species in the plasma transfers energy, leading to the destruction of the crystalline region, which subsequently relaxes into an amorphous form. This intricate process results in a volume difference at the surface and interface [25].

The detailed examination of Fig. 2 and the associated morphological changes provide invaluable insights into the dynamic effects of plasma treatment on the surface characteristics of straw fiber-reinforced PVA composites. The visual representations underscore the complexity of the interaction between plasma and composite materials, paving the way for a nuanced understanding of the enhanced mechanical performance induced by these surface modifications.

### Effect of Plasma Treatment on Mechanical Properties of Composites

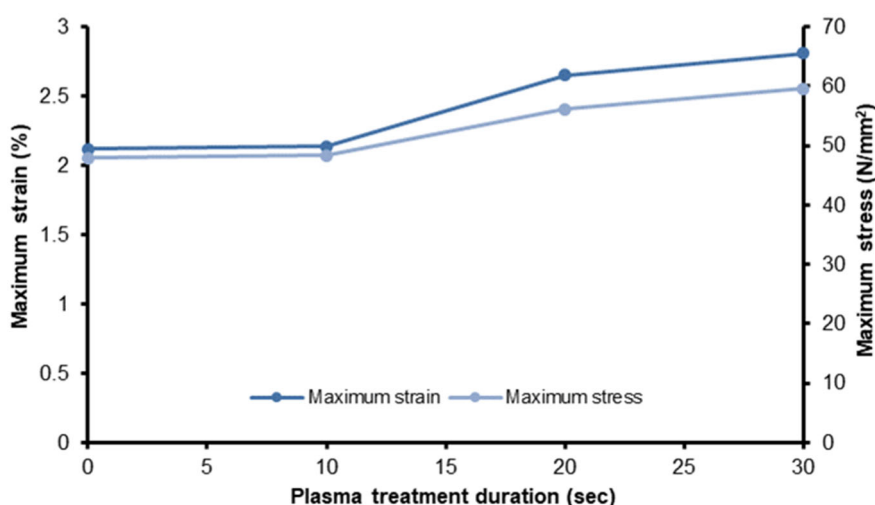
Flexural strength is derived from the maximum flexural stress value that the composite can withstand both before and after fracture. This parameter is

calculated by evaluating the load applied to the material during a flexural test. The flexural strength values, representing the material's ability to resist bending forces, are presented in both Table 2 and Fig. 3 for a comprehensive overview of the material's performance under different conditions. Table 2 and Fig. 3 collectively present compelling evidence highlighting a consistent increase in both maximum stress and maximum strain across a spectrum of composite scenarios, encompassing those subjected to plasma treatment, untreated composites, and those treated for varying durations (10, 20, and 30 sec). This intriguing trend prompts an in-depth exploration of the underlying mechanisms driving these enhancements, thereby enriching our understanding of the complex interplay between plasma treatment and mechanical properties.

The observed increase in maximum stress and maximum strain can be attributed to the profound impact of plasma treatment on the surface characteristics of the composite materials. Specifically, plasma treatment induces a surface modification that

**Table 2.** Maximum strength and maximum strain values

| Parameters specimen | Maximum stress (N/mm <sup>2</sup> ) | Maximum strain (%) |
|---------------------|-------------------------------------|--------------------|
| Plasma 30 sec       | 59.6128                             | 2.80876            |
| Plasma 20 sec       | 56.1720                             | 2.65324            |
| Plasma 10 sec       | 48.3349                             | 2.13582            |
| No Plasma           | 47.8757                             | 2.11737            |



**Fig 3.** Relationship between strain and stress in composites

intricately alters the roughness of the straw fiber. The ensuing changes in roughness levels play a pivotal role in augmenting the interfacial adhesion between the straw fiber and the PVA matrix. These findings align with the work of previous researchers [26], emphasizing the crucial role of surface modification in influencing mechanical properties.

Delving deeper into the mechanisms at play, the augmentation in interfacial adhesion is closely linked to a mechanical interlocking mechanism, as elucidated by the study [26]. This mechanism comes into play due to the inherent surface unevenness between the straw fiber and the PVA matrix. The resulting lock-and-key behavior is a direct consequence of this mechanical interlocking mechanism, fostering a more secure and effective connection between the two materials [27].

Understanding the intricacies of plasma treatment-induced surface modifications and their direct correlation with mechanical interlocking sheds light on the nuanced processes contributing to increased maximum stress and strain. These insights underscore the importance of surface characteristics in composite materials and provide a solid foundation for optimizing their performance in diverse applications. Moreover, these findings contribute to the broader academic discourse surrounding materials science and engineering, establishing a bridge between surface modification, mechanical interlocking, and the

resulting mechanical properties within the context of the existing literature [26-27].

### Function Group Analysis

Fig. 4 provides a detailed FTIR spectrum analysis, offering valuable insights into the molecular composition of the examined composite material. A particularly noteworthy observation is the presence of a pronounced peak spectrum with a remarkably high intensity at approximately  $1730\text{ cm}^{-1}$  indicating the presence of carbonyl C=O stretching. Such C=O groups are commonly encountered in various molecular structures [21], and their prominence in the spectrum underscores their significance in the composite's chemical makeup.

Further scrutinizing the FTIR spectrum, a robust absorption band at  $1260\text{ cm}^{-1}$  becomes evident, pointing towards C–O stretching vibrations. This feature adds another layer to our understanding of the composite's molecular dynamics, highlighting specific vibrational modes associated with the presence of C–O bonds. Meanwhile, the intriguing double peak at around  $700\text{ cm}^{-1}$  in the FTIR spectrum, observed in orthophthalic and isophthalic unsaturated polyvinyl alcohol, can be attributed to the characteristic vibrations of aromatic rings [28]. This double band, present in both orthophthalate and isophthalate unsaturated PVA, is specifically associated with the benzene rings inherent in

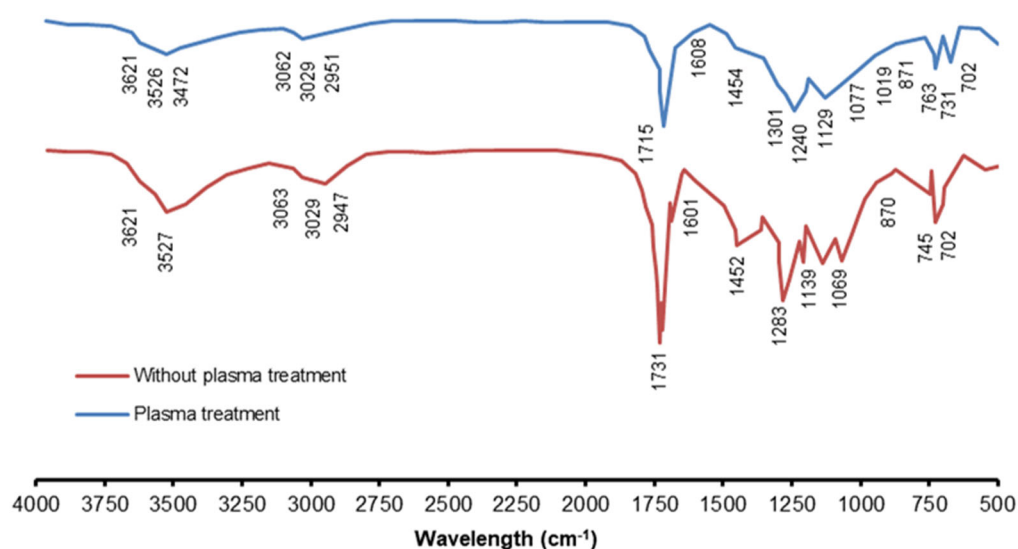


Fig 4. FTIR composites with plasma treatment ( $t = 10\text{ sec}$ ) and without plasma treatment



these compounds [29]. The intensities of the double peak around  $700\text{ cm}^{-1}$  signify the occurrence of two distinct types of vibrations within the molecule, with one exhibiting greater strength or intensity than the other. Notably, aromatic ring peaks at  $3621$  and  $1601\text{ cm}^{-1}$  (for the composite with plasma treatment) and  $3621$  and  $1608\text{ cm}^{-1}$  (for the composite without plasma treatment) further contribute to the intricate molecular characterization.

Additionally, the FTIR spectra reveal variations in the intensities of peaks at  $1069$  and  $1139\text{ cm}^{-1}$  with plasma treatment, indicating enhanced C–O stretching vibrations compared to the untreated composite. Peaks at  $2947$  and  $1450\text{ cm}^{-1}$  correspond to clusters, further adding to the comprehensive understanding of the composite's molecular structure. Notably, the absorption bands in the  $3600\text{--}3400\text{ cm}^{-1}$  region signify the presence of hydroxyl (O–H) groups, with stretching vibrations of the O–H bond being implicated in this spectral range [30]. Fig. 4 suggests no discernible formation of new functional chemical groups within the composite despite the detailed spectral analysis. This observation provides crucial information regarding the stability of the composite's chemical composition and supports a nuanced interpretation of the molecular changes induced by plasma treatment, shedding light on potential applications and optimizations in composite material engineering.

## ■ CONCLUSION

Utilizing cold plasma in the synthesis of composites and combining rice straw as filler with PVA matrix has proven to be a highly effective method for enhancing interfacial adhesion. The augmentation in flexural strength is directly correlated with the prolonged interaction between the fibers and the plasma. Notably, flexural strength exhibited a marked improvement when subjected to plasma treatment compared to untreated counterparts. The application of plasma introduced a discernible roughness effect on the composite surface, and intriguingly, the extent of roughness was found to be influenced by the duration of exposure. Moreover, this rise in roughness was directly associated with an increase

in both the maximum stress value and maximum strain, highlighting the pivotal role of time in shaping the material's mechanical properties. Intriguingly, the results obtained from FTIR spectra analysis revealed that no new chemical groups were formed during the plasma treatment of the fibers. This crucial finding provides robust evidence that the incorporation of plasma technology in composite synthesis does not induce alterations in the internal chemical properties of the material. Consequently, the structural integrity of the composite remains unaffected, reinforcing the viability and stability of the cold plasma approach for enhancing composite materials without compromising their inherent characteristics.

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## ■ CONFLICT OF INTEREST

The authors have no conflict of interest.

## ■ AUTHOR CONTRIBUTIONS

Harianingsih: conceptualization, methodology, writing, review, and editing. Ari Nur Dwi Indriawan: writing original draft and formal analysis. Rizki Setiadi: supervision and visualization. Indra Sakti Pangestu: data curation. Savira Rinda Erliana: project administration. Isnina Noor Ubay: data curation.

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