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"Eco-Optimized Hybrid Composites: Enhancing Mechanical Performance & Gamma Radiation Impact on Fabric-Feather Laminates"

Shah Newaz B. Alam[1] · Muhammad Foyez Ahmed[2,6] ·Majharul Islam[2,6] · J. Ferdaous[3,6] · N. A. Siddique[4] ·Sumonur Rahman[4,6] ·Mubarak A. Khan[5]
✉ Sumonur Rahman
1. Department of Civil Engineering, European University of Bangladesh.
2 Department of Textile Engineering, Port City International University, Chattogram, Bangladesh.
3. Department of Chemistry, Noakhali Government College, National University, Bangladesh.
4. Department of Textile Engineering, Mawlana Bhashani Science and Technology University, Tangail 1902, Bangladesh.
5. Institute of Radiation and Polymer Technology, Atomic Energy Research Establishment, Bangladesh Atomic Energy Commission, Savar, Dhaka, Bangladesh.
6. ITS Labtest Bangladesh Ltd (Intertek), Chattogram, Bangladesh.

Abstract
The increasing volume of poultry waste feathers poses a significant environmental challenge, requiring sustainable waste management solutions. This study investigates innovative methods to repurpose poultry feathers by incorporating biodegradable cotton fabrics to develop eco-friendly composite materials. The research analyses the mechanical characterization and production of laminated composites made from 100% cotton fabric and hen feathers as sustainable substitutes for traditional artificial materials. In this composite were fabricated using a hand lay-up process, linking washed and dried hen feathers with a polyester resin matrix. Tensile, bending, and impact tests were conducted to assess the mechanical performance of these hybrid materials. The addition of cotton fabric enhanced the tensile strength by 35% to 19.6 MPa, increased the tensile modulus by 20% to 0.72 GPa, and made better elongation at break from 6.1% to 7.8%. Impact strength rose by 29%, reaching 10.21 kJ/m², while bending strength doubled from 15.2 MPa to 31.8 MPa. These improvements demonstrate the potential of feather-fabric composites for durable and flexible applications, such as wall panels, acoustic insulation, and furniture padding. Additionally, biodegradability and environmental impact assessments highlight the sustainability benefits of these bio-based composites over petroleum-based polymers, supporting circular economy principles. However, exposure to 500 K radiation resulted in significant mechanical degradation, with tensile strength decreasing from 14.5 MPa to 7.3 MPa for feathers and from 19.6 MPa to 10.8 MPa for feather-fabric composites, indicating structural limitations in high-temperature conditions. These findings emphasize both the potential and challenges of employing biological materials in composite manufacturing. By integrating waste-derived natural fibers, this study advances the development of sustainable, high-performance materials for eco-conscious applications.

Highlights
- *The addition of cotton fabric to a hybrid composite increases its tensile strength.*
- *Feather-fabric composites degrade synthetic use and progress sustainability.*
- *Radiation exposure limits high-temp use by reducing mechanical strength.*
- *Composites could be used for long-lasting, lightweight aesthetic applications.*
- *Hand lay-up procedure was applied using hardener and unsaturated polyester resin.*

Keywords:
Reinforcement with waste hen feathers and cotton fabric, Polyester resin matrix, Sustainable materials, Radiation degradation, Eco-friendly composites.

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I. INTRODUCTION

Industries around the world are increasingly using natural materials as substitutes for conventional synthetic composites in the goal of sustainable development. Innovative, environmentally friendly materials that decrease carbon footprints while keeping high performance are desperately needed, as environmental awareness and regulatory demands have grown. Because of their biodegradability, renewability, and advantageous mechanical qualities, natural fibers have become one of these materials' strongest competitors [1,2]. Keratin is a naturally occurring fiber that shows great promise; it is mostly derived from chicken feathers. Hen feathers are a desirable choice for reinforcing composite materials because they are high in keratin, a fibrous protein with remarkable tensile strength and durability. Poultry by-products are widely available, providing a chance to turn waste into useful resources and advance the circular economy [3,4]. Feather-reinforced composites have demonstrated excellent mechanical performance, according to several studies [5,6,7,8]. These composites can be used for a variety of applications, from lightweight packaging solutions to automobile components. Although composites consisting solely of hen feathers have shown promise, hybridization with other natural fibers, such cotton, can improve their mechanical performance even further. Renowned for their high tensile strength and flexibility, cotton fibers enhance the qualities of keratin fibers, resulting in a synergistic effect that raises the composite's overall performance [9]. By adding 100% cotton fabric, the composite can be made more adaptable for a range of applications by improving impact resistance, ductility, load distribution, and durability [6,10]. A key factor in maximizing the potential of these hybrid composites is the fabrication process. The exact control over fiber orientation and the impregnation of the polymer matrix—typically a thermosetting resin like polyester—is made possible by techniques like compression molding and hand lay-up. Optimizing mechanical qualities requires appropriate interfacial adhesion between the fibers and the resin matrix [11,12,13]. The final composite's performance is influenced by factors such resin formulation, processing conditions, and fiber shape, highlighting. Several research works have demonstrated the efficacy of hybrid reinforcing techniques in natural fiber composites, exhibiting notable enhancements in mechanical attributes like impact toughness, bending resistance, and tensile strength [14,15]. The capacity to strategically combine natural fibers to manufacture composites with specific qualities makes these materials attractive substitutes for petroleum-based polymers, supporting worldwide sustainability objectives [16,17]. In this work, a laminated composite composed of 100% cotton fabric and hen feathers is fabricated and mechanically characterized. This study intends to clarify the performance advantages of combining these two natural fibers by utilizing a small hand lay-up technique and carrying out extensive mechanical testing, including tensile, bending, and impact assessments. As lightweight and durable solutions are essential for improving efficiency and safety in a variety of industries, including automotive, construction, and protective gear, the findings will offer insightful information about the potential applications of feather-cotton composites in these and other fields [18,19]. In the end, by demonstrating the revolutionary potential of using natural fibers in composite manufacturing to promote an environmentally responsible future, our research adds to the larger conversation on sustainable materials.

II. MATERIALS AND METHODS

2.1 | Materials

100% cotton woven plain fabric (60x60/120x65, 80 GSM) and waste hen feathers were collected from the local market in Bangladesh. Unsaturated polyester resin and hardener (MEKP) were collected from Polynt Composite Malaysia.

2.2 | Methods

2.2.1 | Fabrication process of Composites

The fabrication of a lamination composite from hen feathers is an innovative and sustainable approach that utilizes the unique properties of feathers, primarily composed of keratin. To create the composite, feathers are first cleaned, dried, and optionally chopped into smaller pieces. The polymer matrix polyester resin is prepared by mixing it with a hardener. Layers of hen feathers are then arranged on a mould and impregnated with the resin using a roller ensuring complete saturation. This process can be repeated to form multiple layers, building a strong laminate structure. The resin penetrates the feathers confirming a strong bond. On the other sample, composite using hen feathers and 100% cotton fabric is an eco-friendly approach to creating lightweight and durable materials. while cotton fabric adds structural support and flexibility. Both composite samples were fabricated by the modest hand lay-up method, using two glass plates, then placed under a dead weight (approximately 30 kg) at room temperature for at least 24 h for good curing and interfacial adhesion between fibres and polyester matrix (Figure 1). A fabricated hybrid composite is shown in (Figure 2) The average thickness of the hybrid composites was approximately 3 mm.

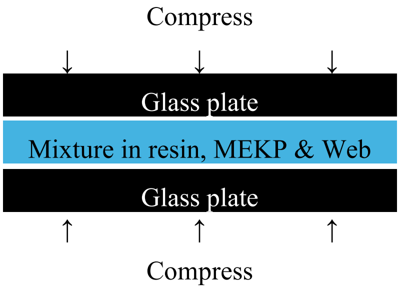

Figure 1 Illustration of applied pressure used in composite consolidation

(a) (b)

Figure 2 Photograph of the composite sample. (a) Hen feathers (b) Hen feathers and cotton fabric

2.2.2 | Characterization

Numerous variables influence the mechanical properties, including the shape of the yarn in textiles, the kind of fiber the fabrication techniques, the reinforcing matrix, the heating and cooling rate of thermoplastic polymeric materials, and more. Furthermore, produced laminated composite panels are also significantly influenced by the fabric qualities (such as density, thickness, yarn count, etc.), morphology, molecular weight, number of plies, and chemical cross-linking. Mechanical Examination Tensile, flexural, and impact tests were used to mechanically characterize the hybrid composite materials. In compliance with ASTM D3039, ISO 14125, and ASTM D256 standards, respectively, the tensile, flexural, and impact tests were carried out. The impact testing was performed using a universal impact tester (Hung Ta Instrument CO. LTD, Taiwan). The tensile and flexural testing was performed using a universal testing machine (UTM) (model: H50KS-0404, Hounsfield Series S, UK). With the impact testing machine, the hammer mass was 2.63 kg, the lift angle was 150°, and the gravity distance was 30.68 mm. A 50 mm span distance and a crosshead speed of 10 mm/min were used in the UTM tensile testing scenario. A crosshead speed of 60 mm/min and a span distance of 25 mm were used for the flexural testing. The following relationship can be used to calculate tensile strength (TS), Equation [1]. A critical parameter in material science:

$$\boldsymbol{TS} = \frac{\boldsymbol{F}\mathbf{max}}{\boldsymbol{A}}$$

[1]

where F_{max} denotes the maximum load applied to the sample and A denotes the sample's cross-sectional area. This strength metric is essential for assessing how resistant a material is to break under tension.

Elongation-at-break (EB), another crucial characteristic that indicates the ductility of the material, is represented as a percentage: Equation [2]

$$\boldsymbol{EB}\ \mathbf{(\%)} = \left(\frac{\Delta L_b}{L_0}\right)\mathbf{100\%}$$

[2]

where ΔL_b is the sample's starting gauge length and L_0 is the extension at the breaking point. This measure sheds light on the material's ability to deform before breaking.

One of the most important parameters for comprehending material stiffness is Young's modulus (E). The stiffness of a material is indicated by its Young's modulus, which is defined as the ratio of stress to strain in the elastic region of its behavior [Figure 3]. The yield point is reached by calculating Equation [3] the slope of the linear portion of the stress-strain curve:

Y = dσ/dε

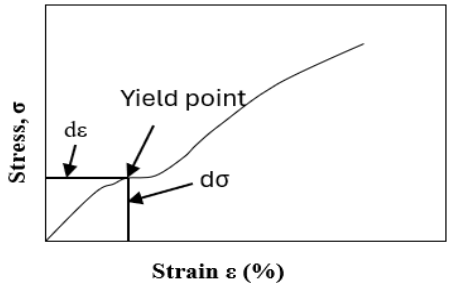

Figure 3 A typical stress-strain curve [3]

where dσ is the stress at yield and dε is the corresponding strain. In applications that call for exact deformation control, this modulus is crucial.

For flexural testing, the maximum load P_{max} applied at mid-span of a sample with support spans distance L is used to calculate flexural stress using the Equation [4]

$$\mathbf{FS = 3P_{max}L/2bd^2}$$

[4]

where the sample's width is denoted by *b* and its thickness by *d*. This property is vital for materials in structural applications where bending resistance is essential.

For impact testing uses a hammer and anvil device to apply a controlled force to a sample to evaluate the toughness of a material. A conversion table provides a measure of impact energy per unit area by recording the absorbed energy, Equation [5]

Impact energy = Kgfcm /width × thickness

[5]

These computations, which include impact, flexural, and tensile evaluations, provide a thorough method for describing the mechanical characteristics of materials, which is vital for selecting materials for engineering applications where toughness, stiffness, and strength are critical.

III. RESULTS AND DISCUSSIONS

3.1 | Mechanical Properties- A comparison of the mechanical characteristics of two composite materials—one composed solely of hen feathers and the other using hen feathers combined with 100% cotton fabric—is presented in the data. The mechanical properties of different reinforced laminated composites are tabulated in Table 1.

Laminated composites	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Elongation & Break %**	**Bending Strength (MPa)**	**Bending Modulus (GPa)**	**Impact Strength** kJ/m²
Hen Feathers/ Polyester resin	14.5	0.60	6.10	15.20	1.20	7.94
Hen Feathers/ Fabric/Polyester resin	19.6	0.72	7.80	31.80	1.80	10.21

Table: 1 Mechanical properties of laminated composites.

3.1.1 | Tensile Strength- The inclusion of cotton fabric raises the tensile strength [Figure 4] of the feather-only composite to 19.6 MPa, a 35% improvement. This suggests that the cotton fabric improves the composite's overall strength and load-bearing capability. Like this, a 20% increase in stiffness is shown by the tensile modulus [Figure 6] which rises from 0.60 GPa for the feather-only composite to 0.72 GPa for the feather and fabric composite. This implies that the hybrid composite is more resilient to deformation when subjected to stress. In addition, the hybrid's elongation at break [Figure 6] rises from 6.1% for the feather composite to 7.8% for it, indicating increased ductility and flexibility. As a result, the composite is more suitable for uses needing both strength and flexibility since it can stretch farther before breaking. Overall, stronger, stiffer, and more ductile material is produced when cotton fabric and hen feathers are combined, providing improved performance for a variety of applications.

3.1.2 | Bending Strength- The addition of cotton fabric to hen feathers significantly improves the mechanical properties of the composite, as evidenced by the findings of bending strength [Figure 5] and bending modulus [Figure 6]. With the inclusion of cotton fabric, the bending strength of the feather-only composite is increased to

31.8 MPa, more than twice its original value. This suggests that by more efficiently strengthening and spreading stresses, the cotton fabric increases the composite's resistance to bending forces. Comparably, a 50% increase in stiffness is reflected in the bending modulus, which rises from 1.2 GPa for the feather-only composite to 1.8 GPa for the feather and fabric composite. In response to bending, this implies that the hybrid composite is less prone to deformation and more robust. A cotton fabric additive strengthens and stiffens the composite, making it more appropriate for uses requiring high bending strength and stiffness, like structural parts for construction or automotive use. The success of mixing cotton fabric and hen feathers to produce a composite with better mechanical performance is demonstrated by these findings.

3.1.3 | Impact Strength- The results for impact strength [Figure 7] show that adding cotton fabric to the composite of hen feathers improves it noticeably. The impact strength of the feather-only composite is 7.94 kJ/m²; adding cotton fabric raises this value to 10.21 kJ/m², a 29% improvement. This implies that the cotton fabric enhances the material's capacity to absorb and release energy during impacts. The fabric reinforces the composite structure by limiting the development of cracks and more evenly distributing impact pressures. The hybrid composite is therefore more resilient and resistant to deterioration from dynamic loads or abrupt shocks. This development makes the feather and fabric composite more appropriate for uses where durability and energy absorption are crucial, including in protective gear, automotive components, or packaging, and where a higher level of impact resistance is required.

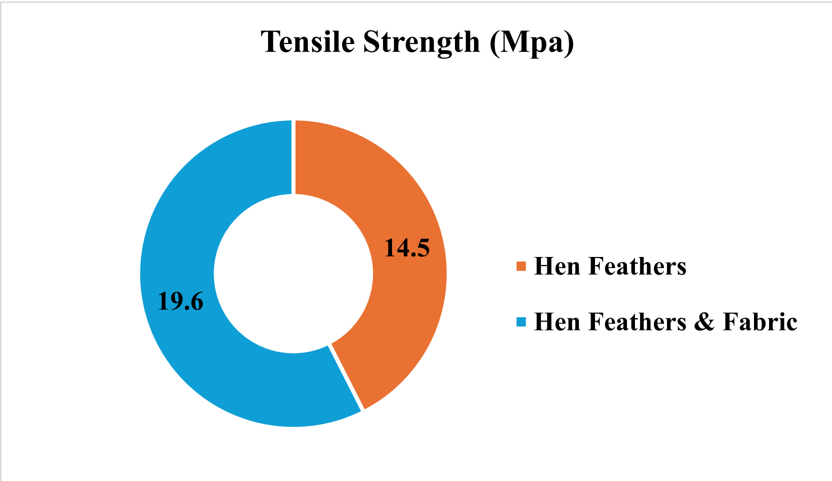

Figure 4 Mechanical properties of composites; Tensile Strength

Figure 5 Mechanical properties of composites; Bending Strength

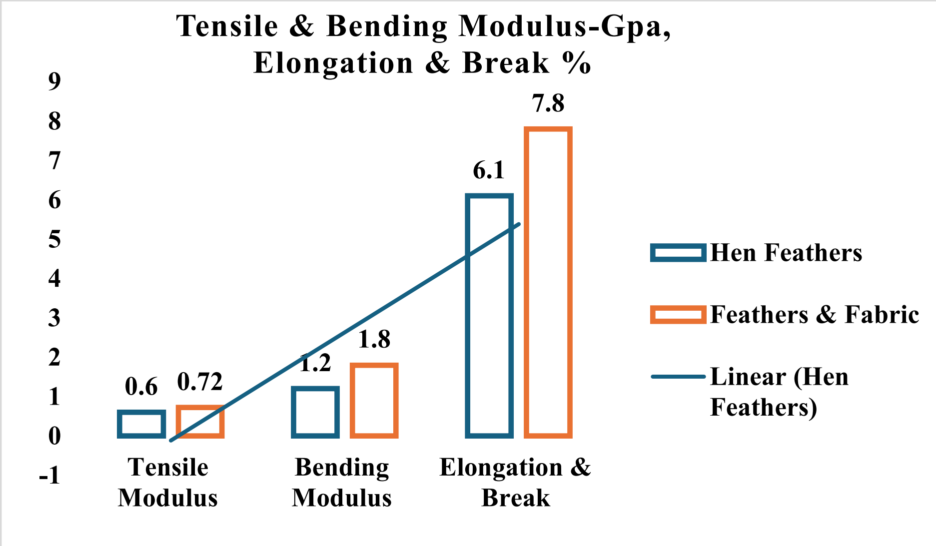

Figure 6 Mechanical properties of composites; Tensile & Bending Modulus, Elongation & Break %

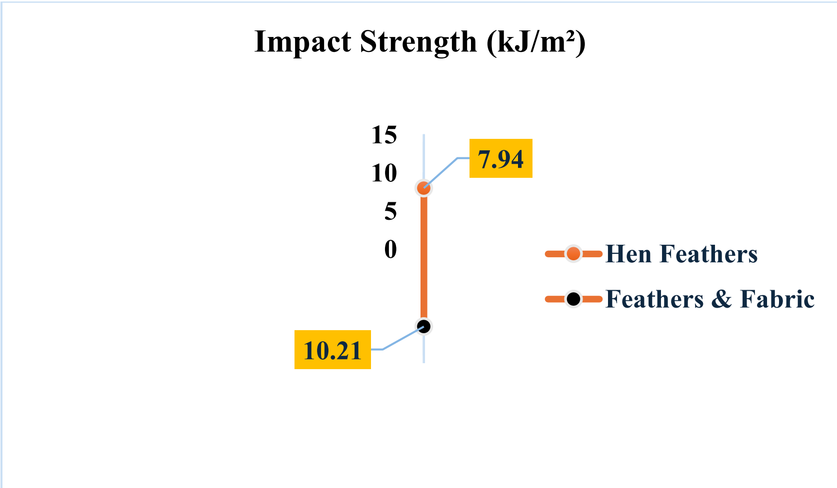

Figure 7 Mechanical properties of composites; Impact Strength

3.2 | Effect of Gamma Radiation

Gamma radiation, also known as gamma rays, and denoted by the Greek letter γ, refers to electromagnetic radiation of an extremely high frequency and therefore consists of high-energy photons. Gamma rays are ionizing radiation and are thus biologically hazardous. They are typically produced by the decay of atomic nuclei as they transition from a high energy state to a lower state known as gamma decay but may also be produced by other methods. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900 while studying radiation emitted from radium. Villard's radiation was named "gamma rays" by Ernest Rutherford in 1903. Natural sources of gamma rays on Earth include gamma decay from naturally occurring radioisotopes such as potassium-40 and as secondary radiation from various atmospheric interactions with cosmic ray particles. Some rare terrestrial natural sources that produce gamma rays that are not of nuclear origin are lightning strikes and terrestrial gamma-ray flashes, which produce high-energy emissions from natural high-energy voltages. Gamma rays are produced by several astronomical processes in which very high-energy electrons are produced. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. A large fraction of such astronomical gamma rays is screened by Earth's atmosphere and must be detected by spacecraft. Notable artificial sources of gamma rays include fission such as occurs in nuclear reactors, and high energy physics experiments, such as neutral pion decay and nuclear fusion. Gamma rays typically have frequencies above 10 exahertz (or >1019 Hz) and therefore have energies above 100 keV and wavelengths less than 10 picometers (10−11 meters), which is less than the diameter of an atom. However, this is not a strict definition, but rather only a rule-of-thumb description for natural processes. Electromagnetic radiation from the radioactive decay of atomic nuclei is referred to as "gamma rays" no matter its energy, so there is no lower limit to gamma energy derived from radioactive decay. This radiation commonly has energy of a few hundred keV, and always less than 10 MeV. In astronomy, gamma rays are defined by their energy, and no production process needs to be specified. The energies of gamma rays from astronomical sources range to over 10 TeV, an energy far too large to result from radioactive decay. A notable example is extremely powerful bursts of high-energy radiation referred to as long-duration gamma-ray bursts, of energies higher than can be produced by radioactive decay. These bursts of gamma rays, thought to be due to the collapse of stars called hyper novae, are the most powerful events so far discovered in the cosmos. Research on how 500 kRad gamma radiation affects polyester-based composite materials shows that exposure to this radiation level affects mechanical properties, mostly via altering bonding and material structure. Up to an ideal dose of around 300 kRad, gamma radiation can initially improve the tensile strength, bending strength, and modulus of polyester composites. After that, greater doses, such as 500 kRad, cause these qualities to deteriorate. This decreases results from the breakdown of polymers, which jeopardizes the material's cross-linking. For example, at moderate radiation levels, irradiated polyester composites reinforced with fibers such as jute exhibit increased stiffness and strength; however, excessive exposure can result in embrittlement and decreased ductility because of polymer chain scission and cross-link breaks [20,21]. By strengthening the cross-linking between the fibers and the matrix, gamma radiation has been demonstrated to dramatically improve the tensile, bending, and impact strengths of jute-reinforced polyester composites. According to [22] studies have shown improvements in mechanical properties, with the best results usually occurring around 300 krad for pineapple composites and 200 krad for jute composites. However, excessive radiation can deteriorate these properties by breaking the polymer chain. Gamma radiation dosages up to a certain threshold (often 100–500 kGy) result in increased durability and resilience under stress for treated natural fiber composites, such jute and sisal. Studies on polyethylene glycol-modified jute composites exposed to gamma radiation indicate that treated fibers exhibit superior elongation and compatibility over untreated ones [23]. This study examines the effects of two days of radiation exposure at 500 K on two samples: "Hen Feathers" and "Hen Feathers and Fabric." In all situations, there is a discernible decrease in the readings taken before and after radiation [Figure 8]. Following radiation treatment, the observed rate for the "Hen Feathers" sample dropped significantly, from 14.5 to 7.3 MPa. Likewise, after radiation, the rate of the "Hen Feathers and Fabric" sample dropped from 19.6 to 10.8. This decrease implies that radiation exposure has an impact on both materials, as the measured property—which may be strength, durability, or another attribute—declines at elevated temperatures. Compared to "Hen Feathers" alone, the "Hen Feathers and Fabric" sample had higher initial and post-radiation values, suggesting that the fabric component might improve the composite sample's measurable property or enhance resistance. Both samples, however, show signs of deterioration at 500 K, which could indicate limitations in functionality or structural integrity in high-radiation conditions.

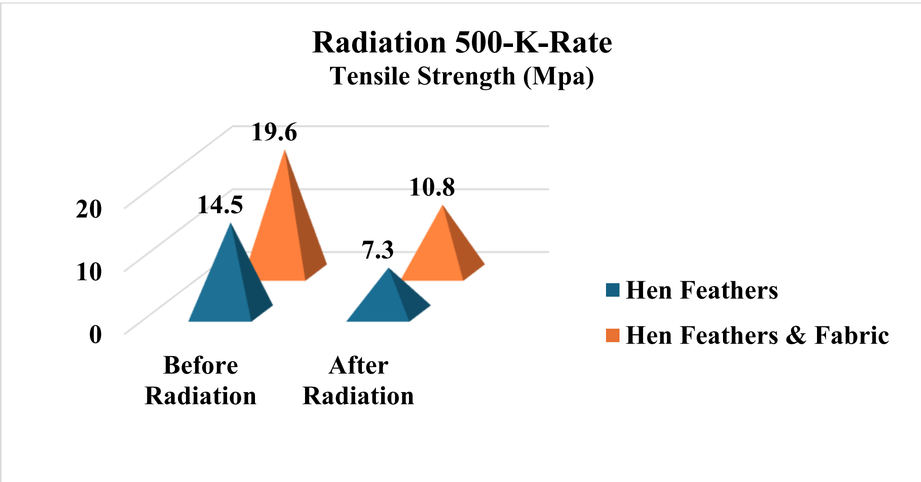

Figure 8 Mechanical properties of composites; Effect of Radiation- Tensile Strength

IV. CONCLUSION

In this study, the data show that, when hen feathers and cotton fabric are combined, a composite material is created that is not only stronger and stiffer, but also much more impact-resistant than one made exclusively of feathers. The higher tensile strength, modulus, bending strength, and impact resistance of the feather and fabric composite demonstrate an improvement in mechanical qualities that renders it a desirable option for a range of demanding applications. Natural fibers like cotton cloth and hen feathers are used in the composite to enhance its sustainability in addition to its functional benefits. As an environmentally beneficial substitute for conventional synthetic composites that use non-renewable resources and pollute the environment, these fibers are renewable and biodegradable. Future research will focus on assessing biodegradability through soil and chemical degradation studies, examining microbial breakdown, moisture absorption, and chemical resistance to better understand its environmental behavior. Additionally, advancements in resin formulations, surface modifications, and hybrid reinforcements will be explored to improve thermal stability and expand its applications in sustainable construction and industrial sectors.

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CONFLICT OF INTEREST STATEMENT
The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT
The data that supports the findings of this study are available from the authors upon reasonable request.

ORCID
Sumonur Rahman (S. Rahman) https://orcid.org/0009-0003-6053-600X

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