Application Of Weibull, ANN And WSN Methods For Assessment Of Performance Of Sustainable Fibres In Green Composites

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Abstract

The research conducted focused on examining the unique properties of Agave Americana Flower Stem fiber (AAFS), particularly its behavior under quasi-static tensile conditions. A total of 200 AAFS fibers were subjected to tensile tests using a standard gauge length of 40 mm. Tests spanned seven groups with quantities (N) ranging from 30 to 200. The study aimed to understand the fibers' mechanical traits, as tensile resistance and modulus of elasticity, and to see how different test quantities influence these properties. A significant observation was the dispersion of the tensile characteristics of AAFS fibers, a common trait of natural fibers. To understand this, we applied rigorous statistical tools, including the Weibull distribution at a 95% confidence interval and one-way ANOVA. A mathematical model was produced utilizing data from experiments regarding the tensile behavior of AAFS fibers. The ANN provided correlation coefficients (R^2) of 0.9897, 0.9971, 0.9993, and 0.9939 for training, validation, testing, and all datasets respectively, which were able to accurately predict the experimental data. The proposed model would be of tremendous assistance to engineers and

designers in obtaining green composite materials that are based on natural fibers and thereby more durable. These methods illuminated the patterns in our results, enriching our understanding of AAFS fiber mechanics.

Key words: Agave americana, Artificial neural network, tensile behavior, statistical methods,

Weibull, statistic, hazard function, Wireless sensor network.

1 Introduction

Natural fibers are becoming more crucial in the packaging industry and in the manufacture of biocomposites [1] because of their environmentally responsible practices in production and consumption, recyclability capacities, and the added value they provide as part of the circular organization [2]. Synthetic fibers made of carbon, glass, aramid, and ceramic are particularly expensive, hazardous, and unsustainable; prolonged exposure can also endanger human health [3]. The use of natural fibers is primarily driven by a concern for both the environment and the economy [4]. As reinforcement for biocomposites, various types of plant fibers including *Jancus efusus* [5], *Ageratina adenophora* [6], *Myriostachya wightiana* [7], *Yucca Treculeana* [8], and *Albizia amara* [9] are brought in use. Natural fibers, such as fibers of *Agave americana*, which are made of lignocellulosic materials, have proven to be excellent candidates for use as a reinforcement in biocomposite materials [10]. Organic strands, however, have a higher absorption rate of moisture. Because they are hydrophilic, they deteriorate at the interface between the matrix and the fiber. As the insertion of absorbent fibers into a hydrophobic matrix is not straightforward, it is essential to improve the adhesion of biocomposites by chemical means to enhance their performance due to low fiber/matrix adhesion [11]. Additionally, the anatomical characteristics of fibers vary between species, which affects their density and mechanical characteristics. The size and quality of natural fibers are influenced by a number of variables, including fiber extraction, storage time, and environmental conditions [12]. According to Belaadi, Bourchak, and Aouici [13], the gauge length (GL), equal to 20 mm, and the number of trials (N = 15 to 40 trials) affect the mechanical properties of sisal fibers. They also noticed that the sisal fiber was very anisotropic, which prompted them to estimate the elastic characteristics of this fiber using the Weibull distribution with two and three parameters and various (index of probability) estimators. Dembri et al. [14] performed a study on the mechanical characteristics of untreated *Washingtonia Filifera* (WF) fiber across five test batches. The data demonstrated an improvement in mechanical characteristics as the number of batches grew from 30 to 150. According to statistical analysis, Kaplan–Meier's estimator best fits the WF fiber, particularly in the 120 tests batch which was found to be the best performer. A one-way analysis (ANOVA) indicated that WF yarns' mechanical characteristics are dependent on the test quantity. Gahgah et al. [15] delved into the effect of test number (N) on elementary sisal yarn mechanical properties, concentrating on modulus of elasticity (E), tensile stress (σ), and rupture strain (ε). After performing static tensile tests over five distinct sets (20, 40, 60, 80, and 100 tests), they found a consistent decline in σ and ε of the sisal yarns as N grew from 20 to 80, with values stabilizing between 148 MPa and 138 MPa for stress and 8.41% to 7.15% for strain at break. A notable drop was recorded for $N = 100$ tests, where the values descended to stress at 135 MPa and break strain at 6.70%. This study revealed that the yarn exhibited optimal mechanical properties at $N = 100$ tests. In terms of modeling the mechanical characteristics, the distribution 2P-Weibull-LS (least square) proved more reliable as compared to the method ML (maximum likelihood). Further, through analysis with a one-way ANOVA, the pivotal influence of N on the mechanical attributes of the sisal yarn was underscored. Gahgah et al.'s findings hold potential significance for the advancement of durable ropes and composite structures, fostering progress in design, performance, and the creation of innovative materials and methodologies in related sectors. A statistical model was developed by Wang et al. [16] to investigate the behavior of uncertainty tension for 30 threads of jute fiber of 100 mm gauge length (GL), taking into account the impacts of property distribution and fiber crimp. A probability distribution function pertaining to the beta function for fiber strain was utilized to depict the statistical characteristics of the crimped jute fibers. While the yarn strength and effective modulus of elasticity had a normal distribution, the tensile plots of comparable yarn samples displayed features that were in line with the beta distribution observed in crimped strain. With reference to the variability in the nonlinear tensile behavior of jute fibers, this observation may make forecasts more accurate. Tensile properties for 13

sets from 30 raw and processed jute yarn specimens having surface twist angles varying from 11° to 13° and a 267 tex linear density measured with GL = 50 mm have been statistically characterized by Saaidia et al. [17]. Different NaOH (sodium hydroxide) concentrations and immersion times were applied to the jute yarns. For the statistical analysis, Weibull approaches with two and three parameters were employed. The results show that there is variation in the failure strain, stress, and modulus of elasticity in uniaxial tensile strands, which is largely influenced by immersion period and concentration of NaOH. Optimal mechanical characteristics were attained with an immersion period of 2 h and a 2% NaOH dosage. Belaadi, Amroune, and Bourchak [18] investigated the impact of the sodium bicarbonate (NaHCO$_3$) on vegetal flax fibers mechanical characteristics. Their focus was on crucial mechanical attributes like tensile stress, break strain, and modulus of elasticity. The study found that a 20% NaHCO$_3$ treatment over a period of 120 h enhanced the fibers" mechanical performance. Specifically, there was a 43% increase in tensile strength and an 81% rise in Young's modulus relative to the untreated samples. The researchers employed the Weibull distribution for their analysis, which indicated marginally elevated values for the chemically treated fibers. An ANOVA assessment was also conducted, confirming the significant influence of varying NaHCO$_3$ concentrations on flax fiber mechanical behavior. With a gauge length, GL = 40 mm baseline length, the average mechanical characteristics of the fibers (WF) were found to be 119.3 ± 86.28 MPa for tensile strength, 20.55 ± 11.08 for ultimate strain, and 2.34 ± 1.36 GPa for Young's modulus. A SEM (scanning electron microscope) analysis of various Washingtonia biomasses was conducted recently. They came to the conclusion that Washingtonia fiber holds a great deal of promise for use as a biomaterial in the future for a variety of purposes. Amroune et al. [19] explored the influence of gauge length on the mechanical attributes of flax fibers, specifically UTS, modulus of elasticity and failure strain. The research discovered that as gauge length increased, there was a reduction in fiber stress and strain at break. Anisotropic properties were evident in the flax fibers, corroborating previous studies on jute fibers. The 2-parameter Weibull model closely mirrored the experimental results compared to the 3-parameter version. Notably, flax fibers tested at different gauge lengths (50 mm vs. 30 mm) showed varied modulus values. The study emphasizes the importance of gauge length in evaluating flax fiber mechanics and recognizes the 2-parameter Weibull model as an effective analytical approach.

For optimal use of *Agave americana* fibers in load-bearing applications, a direct assessment of their mechanical properties is essential. While there is ample research on synthetic fibers, using statistics techniques that evaluate natural fibers' mechanical traits is still in its infancy [20]. The primary goal of this study is to examine the tensile behavior of fibers from Agave americana flower stalk samples that vary in size. In this study, two-parameter Weibull statistics along with ML and LS prediction approaches are used to investigate the tensile properties of 200 AAFS fiber samples as the first time. The authors state that this is the first evaluation of this new fiber for samples of different sizes. Additionally, a thorough artificial intelligence prediction was performed for this fiber's tensile characteristics, which were then compared with available data.

2 Technical details

Fibres have been extracted from The *Agave Americana. The fibres have been tested for tensile strength and surface properties studied by use of SEM.* [21]. The weibull method of statistical analysis has been applied to study the mechanical properties of the fibre. [21-24]. The following equations have been derived using the weibull distribution

$$P(x \mid \mu, \alpha) = \frac{1}{\sqrt{2\pi}s} e^{-\frac{1}{2}\left(\frac{x-\mu}{\alpha}\right)^2} \quad (1)$$

$$\varphi = \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} \quad (2)$$

$$P(x \mid \xi, \lambda) = \frac{1}{x\xi\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(x)-\lambda}{\xi}\right)^2} \quad (3)$$

$$F(x \mid s_0, s, m) = 1 - e^{\left[-\left(\frac{x-s_0}{s}\right)^m\right]} x \geq s_0 \quad (4)$$

$$F(x \mid s, m) = \frac{m}{s}\left(\frac{x}{s}\right)^{m-1} e^{\left[-\left(\frac{x}{s}\right)^m\right]} \quad (5)$$

$$F(x \mid s, m) = 1 - e^{\left[-\left(\frac{x}{s}\right)^m\right]} \quad (6)$$

$$\ln\left[\ln\left(\frac{1}{1-P}\right)\right] = m\ln(x) - m\ln(s) \quad (7)$$

where s_0, a location parameter, reflects the parameter × mean value (minimum lifetime), $s > 0$ is the parameter scale (typical value) and m is the parameter shape, also known as the Weibull modulus, are all real positives ($R > 0$). Additionally, the parameter s_0 in our study indicates the distinctive mechanical characteristics, specifically σ_0, ε_0, and E_0, which are, respectively, distinctive tensile stress, failure strain, and the modulus of elasticity.

(m,slx1,…………..x2=∏i=1nFxi=∏i=1nms(xis)m−1e[−xs)m(8)

Minitab software version 16 was employed [25]..

ANN has been used to combine various input variables and predict output [26]. The learning process provides the information exchanged across the neurons or linked node. The model was trained and tested using the MATLAB software program [27].

Tensile properties of AAFS fiber

AAFS fibers were tensile tested in an ambient environment at 1 mm/min. The fibers were distributed in seven batches containing 30 samples each, resulting in an aggregate of 200 randomly chosen elementary fibers from a particular lot, all of which were measured at GL = 40 mm. The stress–strain results of these 30 AAFS fibers test have been analyzed. Notably, the wide range of variability present in natural fibers emphasizes the necessity of thorough statistical analysis. Similar patterns were observed in *Washingtonia Filifera* [28]. In, a thorough statistical study is obviously necessary given the wide range of outcomes, a phenomenon unique to natural fibers. For flax fibers, this behavior was noted at GL = 20 mm in the studies by Belaadi, Amroune, and Bourchak [29]. In , the strength–deformation relationship of AAFS fibers under tensile stress is illustrated. This curve highlights a two-phase behavior typical of cellulosic fibers. Initially, as tension is applied, the fiber exhibits a nearly straight-line response, representing the fiber's overall stretch and the internal realignment of its microscopic structures called fibrils. As the test progresses, the fiber resists the pull with a more pronounced straight-line behavior right up until it breaks. Interestingly, just before the breaking point, the fiber shows a brief period of increased resistance or elasticity, suggesting its inherent resilience against the applied force. The first phase, which represents a non-linear zone for strains between 0% and 0.8%, is followed by the second phase, which is represented by a dramatic fall in stress at a mean value of 45.92 MPa, corresponds to the failure of the specimen. The elastic region on the graph was used to calculate the modulus of elasticity for strains between 0.3% and 0.8%.

The results of research on natural fibers have been compared and published in the literature. Because of the various parameters influencing vegetable fiber production, the comparison of their mechanical characteristics is difficult. The σ, ε, and E values obtained in this work surpass those found in previous research [30-35]. This is because previously there were fewer tests conducted than in our study, which involved 120 samples. For σ, ε, and E, for AAFS fibers, the experimental findings were 50.73 MPa, 1.59%, and 4.25 GPa, respectively. In this study, AAFS fiber with a gauge length of GL = 40 mm was found to have a higher tensile stress than *Myriostachya wightiana* fiber (46.554 MPa) [36], and lower than that of *Juncus effusus* fiber (113 ± 36 MPa) [37]. The measured gauge lengths are 20 and 40 mm, respectively.

Statistical analysis of AAFS fiber data

Due to the diversity of the mechanical properties of plant-based cellulose fibers, it is difficult to design composite structures. To appreciate the advantages of biocomposites, or threads formed from vegetable fibers, understanding the factors that improve their performance is essential. A 95% CI predictive performance model is used in to illustrate the variation in the link between the power fit, Young's modulus, and tensile strength vs. rupture strain. The modulus of elasticity decreases as the resistance increases, as is illustrated above, also a similar trend is observed in the relationship between rupture strain and modulus of elasticity. According to different distribution methods, the experimental histograms of mechanical characteristics, specifically for tests N = 200. The normal square root rule has been used, taking into account the quantity of data to be analyzed, to choose the cells needed for the histogram. There are several statistical distributions available in the subject of material science; the three most commonly used in material research to characterize different material properties are the normal distribution, the Weibull distribution, and the lognormal distribution. Indeed, the Weibull distribution is widely used for resistance prediction as well as for assessing fragile rupture, whereas the use of lognormal distribution is limited to represent the particle size and cracking of material. However, the normal distribution is a flexible distribution that may be utilized to characterize random phenomena and mimic a variety of material properties.

Tukey plots showed the mean AAFS mechanical properties, such as strain, modulus of elasticity, and tensile strength, varying with sample number. The box diagrams employed display the overall patterns of the group responses. The distribution of responses and additional features, including mechanical characteristics of a group's responses, can be shown graphically in box plots. In AAFS fibers' mean mechanical characteristics vary as a function of sample number. These parameters are represented by Tukey plots (box plots). Quantiles (Q1 and Q3), the maximum, minimum, median, and median of the variable values constitute this representation. As an example, the median, Q1, Q3, minimum and maximum values of the samples for N = 120 are (46.35, 42.85, 53.47, 18.67, and 151.37 MPa) for stress, (1.43, 1.13, 1.79, 0.01, and 4.02%) for strain, and (3.57, 2.75, 4.66, 1.09, and 11.14 GPa) for Young's modulus.

Kolmogorov–Smirnov and normality trials

Kolmogorov–Smirnov method was utilized to perform a series of normalcy tests as part of our inquiry into the material qualities of AAFS fibers. A significant p-value of 0.010 in the results has been observed for the constraint of AAFS fibers. Since this result is less than the traditional cutoff of 0.05, the assumption of a normal distribution of data is rejected. This indicates that the natural fiber constraint data is not regularly distributed. Furthermore, 2.62 was found to be the skewness parameter for this dataset. This level of positive skewness indicates a strongly skewed distribution to the right. This implies that in AAFS fibers, there are more occurrences of extraordinarily high constraint values than in low ones. Additionally, comparable non-normal patterns were found in the break strain and modulus of elasticity. With p-values of 0.010, both parameters showed substantial deviations from normalcy. A positive skewness was also shown by their respective skewness values of 1.40 for break strain and 1.79 for modulus of elasticity. This corroborates the finding that AAFS fibers can show very high values for break strain and modulus of elasticity. When combined, these results have significance for the investigation and application of these organic fibers. These important metrics have a non-normal distribution, which might affect the choice of relevant statistical studies and offer a more

complex understanding of the intrinsic AAFS fibers. Therefore, a Weibull distribution as well as a lognormal distribution can all be used to characterize the property dispersion. Thus, it is imperative to ascertain which of these three principles most accurately characterizes the outcomes of the experiment.

The Anderson–Darling test findings for various distributions applied to a material's tensile resistance, failure strain, and modulus of elasticity are shown. The p values below 0.05 show that there were substantial deviations from every distribution seen overall. With an AD value of 8.350, the lognormal distribution turns out to be the best fit for the tensile resistance. Likewise, failure strain and modulus of elasticity showed AD values of 1.347 and 4.581, respectively, and were also in close alignment with the lognormal distribution. In later investigations, care is recommended since, although certain distributions more closely resembled specific material qualities, none offered an ideal approximation for any of the characteristics.

AD adjustment quality of AAFS fiber normality data

The intricacies in the data become more apparent as the AAFS fiber properties are analyzed across several distributions. The lognormal distribution is frequently found to be the most suitable for tensile strength; this is especially true for sample sizes of 200, as seen by its AD value of 8.350. The strain at break displays a varying agreement with distributions; for sample sizes of 120, in particular, the lognormal is prominent with an AD value of 4.665. When evaluating Young's modulus, the data indicates a clear trend: the AD values for the normal distribution progressively grow with sample size, reaching a peak of 9.454 for a sample size of 200. On the other hand, the behavior of the lognormal and 3P-Weibull values varies with size. Interestingly, with 200 samples, the lognormal achieves an AD value of 1.347, indicating that it may be a suitable descriptor. All together, these findings highlight how complex the material's properties are, with the lognormal distribution typically providing the most accurate depiction across a variety of parameters. The information emphasizes the necessity of a comprehensive strategy that strikes a balance between statistical and empirical insights when analyzing AAFS fiber properties.

The AAFS fiber strength, strain, and modulus of elasticity were examined in this work by using the Weibull function with two, which showed a considerable degree of variance. Based on Weibull-LS and ML, nevertheless, it is perceived that the two-parameter Weibull lines for both the LS and ML estimation methods () for the AAFS fiber appear to have a reasonable fitting line. The experimental values fit in a quasi-linear fashion, with a slight offset from one another. This behavior has been reported by Belaadi, Bezazi, Maache, et al. in the case of sisal fiber and by Bezazi et al. for *Agave Americana* fiber. The statistics results for the two-parameter Weibull distributions are shown in and respectively.

These are measured using five different estimators: Modified Kaplan–Meier, Mean Rank, Median Rank, and Kaplan–Meier. Weibull modulus fit and variability are explained by correlation coefficient R^2 values. The correlation R^2 varies from 0.863 to 0.939 for tensile strength, from 0.842 to 0.97 for strain at break, and from 0.957 to 0.987 for Young's modulus based on and the 2P-Weibull analysis. Upon closer inspection, the Kaplan–Meier estimator stands out from the others since it consistently displays the highest R^2 correlation coefficient among these estimators.

The parameters, forms, and defining values for the Weibull distribution of each mechanical property have been presented. For the 2P-Weibull-ML model regarding deformation (m_ε), strength (m_σ), and modulus of elasticity (m_E) at varying values of N (30, 60, 90, 120, 150, 180, and 200): m_ε values were 2.274, 2.591, 2.612, 2.372, 2.435, 2.412, and 2.352; m_σ values were 4.419, 2.801, 2.846, 2.977, 2.808, 2.483, and 2.547; and m_E values were 2.348, 2.162, 2.243, 2.279, 2.061, 1.951, and 1.976, respectively. The probability of survival of mechanical characteristics, specifically tensile resistance, fracture strain, and modulus of elasticity, based on different LS and ML estimation methods. It has been observed that a good alignment with the experimental results. The survival probability was plotted using parameters derived from the Weibull global distribution. The estimating error is nearly negligible, thanks to the availability of a large dataset (200 tests). In , the probability of survival of the traction resistance is depicted and traced using the estimation method of least squares, coupled with Pi = i/n +1. With two sets of parameters from Weibull at *N*= 60, 120 and 180, the values are detailed as: m_σ = 4.547 with σ_0 = 58.16, m_σ = 5.277 with σ_0 = 53.60.19, m_σ = 4.580 with σ_0 = 57.48.

Similarly, the results for break strain and modulus of elasticity also display consistency. The Weibull parameter values correspond closely to those cited in the literature for cellulosic fibers, where the Weibull modulus typically falls between 1.5 and 4.5. further highlights that at a 50% survival probability ($P(\sigma) = 0.5$) for AAFS fibers, the projected ultimate tensile strength is approximately 39.7 MPa and 36 MPa, respectively, for $N=60$ and 120. This closely matches the average experimental value calculated at $\sigma = 53.72$ MPa. Moreover, the values recorded were 1.59% for strain at failure and 4.25 GPa for modulus of elasticity at $P(\varepsilon) = P(E) = (0.5)$.

ANOVA analysis of the AAFS fibers' mechanical characteristics

Statistical methods of data analysis provide a means of improving comprehension and analysis of the experiment's importance. Based on the data's mean and distribution, one-way analysis of variance (ANOVA) was applied in this study to estimate the population samples. According to the first hypothesis, there is no statistical difference between any two-sample means, or they are all the same. Furthermore, the selection of the sample is influenced by the quantity of fibers. P, Fisher's test, MS, SS, and CI were therefore used to perform the ANOVA in order to determine the effect of the test number on these results and to better describe any mechanical property parameters.

The findings from one-way ANOVA have been presented for the mechanical properties of AAFS fibers across each of the groups (30, 60, 90, 120, 150, 180, and 200) at a confidence of 95%. Since the p value = 0.000 ($p < .001$) is below the threshold of significance of 0.05, therefore the null hypothesis which assumes that the means would be equal cannot be upheld.

ANN modeling of AAFS fibers

Because of its outstanding performance in feedback networks, the Scaled Conjugate Gradient (SCG) back propagation algorithm was employed for a system to learn throughout this experiment. Three categories were created from the data utilized in this study's experiments: 20% served for validation, 10% during the test set and data, and 70% were put into the neural network during successive training phases. For the ANN design that simulated the behavior of AAFS fibers, the SCG was chosen. The ANN model's architecture topology for the behavior of AAFS fibers has been determined. The performance graph illustrates how the errors that are occurring in the network disappear. The progression of each epoch, which can be best understood as the last cycle of the entire neural network information set, was used to determine these mistakes. When the lowest error value is reached, the training immediately ends. It is demonstrated that, for the tensile behavior of AAFS fibers, the average error decreases mostly systematically up to 9 epochs (iterations). In contrast, a supplementary increase in iterations lengthens the training duration while keeping the error quantity constant. This result validates previous research by different investigators on the application of ANN for process modeling and forecasting. As seen, the region of zero error and its vicinity exhibits the fewest mistakes. The minimal error rate of the neural network training stage serves as a sign that the procedure was completed effectively. Based on the determination coefficient (R^2) obtained for training, testing, validation, and all datasets (0.9971, 0.9993, 0.9881, and 0.9939), respectively, are shown, the network is chosen for model prediction as depicted in $\varepsilon Tran = \log \varepsilon - 0.11/1.57 - \varepsilon$. The best predicting ability of the created model is therefore indicated by the neural network model's more important features in the validation. The testing phase was used to measure the neural network models' accuracy in predicting unknown data.

To ascertain if the ANN models correctly reflected the non-linear nature of the AAFS fiber behavior, graphic and statistical investigations were conducted. shows a comparison of the ANN models' results with the experimental values. The figures demonstrate a very good fit between the experimental data and all of the proposed response models. Although the ANN was able to evaluate the processes' predictability, the ANN model with 10 hidden neurons proved to be the most effective. The ANN's capacity to handle any kind of non-linearity explains this outcome.

Conclusions

In order to identify which of the seven tested batches provides the greatest performance, the current work evaluated mechanical parameters such as E, ε, and σ by examining the AAFS fiber condition. The study's primary findings include an increase in the average values of σ and E as well as a rise in batch count from 30 to 200. According to the estimation techniques obtained by LS and ML approaches in the statistical study, it appears that the AAFS fiber is better fitted by Kaplan–Meier estimator. Based on the experimental results, it seems that the fiber AAFS's highest mechanical properties were attained for $N = 180$ trials. In addition, the ANN technique was also used to predict the tensile strength. One-way ANOVA results showed that N exhibited a significant effect on the mechanical characteristics of the AAFS fiber. Regression analysis using artificial neural network demonstrated higher accuracy with a precision of more than 95%. The average experimental tensile behavior data for $N = 180$, which provided the ideal conditions, showed extremely good agreement with the anticipated response patterns. Researchers and designers would find the suggested model to be very useful in obtaining natural fiber-based green composite products.

Highlights

- Agave Americana flower stem fibers (FSAA) are being studied for their potential use in polymer composites.
- Tensile tests were conducted on 200 FSAA fibers.
- The variability of the results was analyzed and quantified using statistical methods and an artificial neural network (ANN).
- The ANN was able to accurately predict the experimental data.
- For each tensile property, the ANOVA test was performed to assess the seven groups.

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