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Characterization on Physical, Mechanical, and Morphological Properties of Indian Wheat Crop

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Abstract: The absence of scalable and economically viable alternatives for managing residues coupled with shorter planting window and growing labour shortages and energy prices requires a sustainable solution for the crop residue management in northern India. As per "Need of the Hour", the present research work focused on physical, mechanical, and morphological characterizations of wheat, which will help in further design of the low-cost straw combine. For this purpose, two varieties of wheat (HD-2967 and WH-1105) were used for the present study, as these are the prevalent varieties of Haryana state. The straw specimens were collected at harvesting period from a farmer's field, which is located at a longitude of 75.64 and latitude of 29.15. The physical characterization of the crops was conducted on the basis of diameter, length, and thickness of nodes of straws. In contrast, the mechanical characterizations was performed by calculating the tensile and shear strength of the straws. The morphological analysis was performed by using field emission scanning electron microscopy (FESEM). The energy dispersive spectroscopy was performed to analyse the presence of constituting elements of straw. The statistical analysis showed that moisture content in the straw had a significant effect on tensile strength and shear strength.

Keywords: energy dispersive spectroscopy; moisture; shear strength; tensile strength; wheat straw

1. Introduction

Sustainability in agriculture can be defined as farming in sustainable way without compromising the environment and resources of future generations to meet their needs. The sustainable food system can be generated by the improving the crop residue management and farming practice. The traditional farming practice causes environmental and soil behaviour changes because of burning of crop residuals. In the northern part of India, wheat is one of the vital food grains, which is rich in nutritional ingredients such as protein, vitamins and carbohydrates and provides balanced food [1]. The small states of Haryana and Punjab, often referred to as the "Food Bowl of India" contribute to about 69% of the total food output in the country (about 54% and rice 84% wheat) [2,3]. With the advent of the Green Revolution in India, combine harvesters were introduced in Haryana and Punjab for the harvesting of paddy and wheat [4] and became famous by the beginning of the 21st century. Currently, more than 75% of the area of both the crops is combine harvested in both the States and is increasing every year due to shortage of farm labour. The labour scarcity is very high during the harvesting period of wheat and rice, as the agricultural labour has been migrating to cities for other off-farm activities such as industry, transportation, building, and construction [5–7], and one of the main reasons for the introduction of combine harvesters [8]. Combine harvesting leaves a large amount of loose and anchored crop residue in the field. The leftover straw of wheat after harvesting by combines is collected with ease using straw combines [9,10] and balers [11,12], and is generally used as animal feed [13]. Wheat straw can also be used to make paper and produce particleboard in different densities as it contains a large amount of fibre [14–16]. This can reduce wood consumption and ease excessive deforestation. Wheat straw also has excellent thermal and sound insulation properties, and thus can be used in construction [17].

Moreover, the high energy content in wheat straw can be used in thermochemical conversion processes such as pyrolysis [18,19], combustion [20–22], and gasification [23,24]. The increase in photosynthesis productivity can also increase yield significantly by unintended enhancement of leaf anatomical and biochemical behaviours comprising lenience to non-optimal temperature circumstance [25]. The various researchers have worked on the physical and mechanical properties of different varieties of wheat. Annoussamy et al. [26] concluded that bending strength and shear strength decreased by 70% and 80% with decomposition (wheat straw) due to the loss of mass and change in biochemical composition (mainly loss of cellulose), whereas, straw moisture had opposite effects and bending stress decreased by 54% and the shear stress increased by 83%. Afzalinia and Roberge [27] observed that coefficients of friction for a wheat straw at 10% moisture content and green barley at 51% moisture content were 0.13 and 0.21, respectively, on a polished steel surface. Esehaghbeygi et al. [28] observed that the shearing stress of wheat stems decreased as the moisture content decreased, and cutting height increased. Chandio et al. [29] concluded that shear strength, specific shearing energy, and cutting force of wheat straw increased significantly with increased loading rate.

Chandio et al. [30] concluded that when loading rate increased, the bending strength of wheat decreased from 23.93 to 7.49 MPa, shearing energy risen from 124.28 to 265, and Young's modulus decreased from 1.20 to 0.22. It was concluded that shearing energy could be saved considerably by reducing the loading rate on wheat toward first, second, and third internode's positions. Sarauskis et al. [31] concluded that 160 N force was needed to break fresh straw of winter wheat as compared to 53 N for spring barley straw. To cut the new straw of winter wheat and spring barley at the node, 35 to 43 N weaker forces are required compared to cutting at other sections of the straw. Hussain et al. [32] analysed morphological properties along with carbohydrate accretion in the stem of various soybean genotypes under variable light atmosphere. In addition, the stem resistance of genotypes varies with variable planting patterns [33].

Due to the lack of sustainable solutions, the farmers in the north India region have chosen the 'Burning Way' of managing the residues, which has led to a significant increase in farm fires. This has resulted in multiple problems of soil health deterioration, air pollution-induced human health issues, loss of biodiversity, diminishing farm profits, and other problems. Keeping in mind the economic constrains, there is an urgent need to design and develop a machine for straw management that is farmer-friendly, economical, and has options of removing or leaving full/partial residue from the field. The presented manuscript is a part of a project that is working on a sustainable solution of crop residue burning. The core aim of this research was the development of straw combine that can be applied to various crops, especially wheat and paddy. For this purpose, it was necessary to characterize the crops on the basis of moisture and individual strength. The wheat variety 1105 and 2967 are preferred crops in the northern part of India. The harvesters used for these crops sometimes face breakdown during harvesting of 1105 in the long duration as compared to wheat 2967. The wear and tear of blades of the harvester affects the efficiency of machine and productivity of the field. To locate the root cause of the problem, this research paper deals with the analysis of physical, mechanical, and morphological properties of the wheat variety 1105 and 2967.

2. Materials and Methods

Two varieties of wheat (HD-2967 and WH-1105) were selected for the current research, as these are the predominant varieties of Haryana state. The straw specimens were collected at harvesting period from a farmer's field that is located at a longitude of 75.64 and latitude of 29.15. The physical properties were measured by cutting wheat stems manually from ground level and specimen samples were selected randomly. The tensile strength of straws was measured using a universal testing machine for texture analyser (TA.XT.plus). TA.HDplusC was used to analyse the shear strength of the straws. Field emission scanning electron microscopy (FESEM) was used to assess structural and rudimentary information at magnifications of 10x to 300,000x, with virtually unrestricted penetration of arena. The experiments were conducted in the laboratory of the Department of Farm Machinery and Power Engineering, CCS Haryana Agricultural University, Hisar; the laboratory of the Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana; and the laboratory of the Mechanical Engineering Department, Indian Institute of Technology, Delhi, during the year 2019. The various parameters used for the analysis are tabulated in Table 1.

Table 1. Parameters and their levels.

Parameter	Nomenclature	Level				
Nodes	N	N1	N2	N3	N4	N5
Moisture Content (%)	M	20	35	50		
Variety	V	V1	V2			

2.1. Characterization of Physical Properties

The wheat properties can be affected by the various factors such as the type of soil, type of irrigation, and climatic variations. Earlier published research states that the height of the plant can be significantly increased by providing three irrigations at 25, 40, and 55 DAS [34]. In addition, there is a 40% loss in wheat crop yield due to lack of nutrient scarcity and presence of metal content in the soil [35,36]. The wheat stems were cut manually from ground level and specimen samples were selected randomly. The internodes were detached as per their location down from the ear [37]. Four internodes of wheat and paddy stalk, namely, first, second, third, and fourth internodes were studied in this research. The fifth and other stem internodes from the straw were not considered because these internodes are usually left on the field [38–40]. In each internode position, internode length (to the nearest 1 mm), mass (to the nearest 0.1 mg), its major and minor diameter and thickness of the elliptical wall (to the closest 1 μm) were measured using a digital caliper with the accuracy of 0.01 mm. The internode diameter of the stem (mm) was converted to the cross-section area in square millimetres. The measurement was performed using the following equation:

$$A = \frac{\pi . t}{2}[a + b - 2t] \quad (1)$$

where A is the cross-sectional area of the stem in square millimetres, and a, b, and t are the major diameter, minor diameter, and thickness of stem in millimetres, respectively.

2.2. Characterization of Mechanical Properties

2.2.1. Tensile Strength

The ability to resist load is generally termed as mechanical strength of the material, and in the present work, the mechanical strength of the straws in the form of tensile testing was checked on the texture analyser machine, as shown in Figure 1. The tensile strength of straws was measured using a universal testing machine for texture analyser (TA.XT.plus). Five identical test specimens were tested with a minimum length of 5 cm. For testing of samples, 2 KN load cell was used with crosshead 0.5 mm/min. At least 5 samples were tested for each straw [41,42].

Figure 1. Texture analyser TA.XTplusC.

2.2.2. Shearing Test

The shear strength of the wheat straw was measured as per the earlier test conducted by [43,44], whereas, for paddy straw, the shear strength was calculated as [45,46]. The internodes of different diameters were accommodated by drilling holes of variable diameter through plates. The shear box was mounted in the tension testing machine to apply shear force on the straws (Figure 2). The loading was applied in a vertical direction [47–49]. The shear failure stress (or ultimate shear strength), τ_s, of the specimen was calculated from the following equation [46]:

$$\tau_s = \frac{F_s}{2A} \tag{2}$$

where, F_s is the shear force at failure (N), and A is the wall area of the specimen at the failure cross-section (mm^2).

Figure 2. Texture analyser TA.HDplusC.

2.3. *Morphological Inspection*

The surface analysis of the straws was performed with the help of field emission scanning electron microscopic (FESEM). The characterization of the elements present in the straw was performed with the help of energy dispersive spectroscopy.

2.3.1. Field Emission Scanning Electron Microscopy (FESEM)

Field emission scanning electron microscopy (FESEM) offers structural and rudimentary information at magnifications of 10x to 300,000x, with practically unrestricted penetration of field, as shown in Figure 3. As compared with conventional scanning electron microscopy (SEM), field emission SEM (FESEM) gives indistinct, fewer electrostatically slanted imageries with a spatial resolution three to six times better. A field-emission cathode in the electron gun of a scanning electron microscope gives slenderer penetrating beams at low as well as high electron energy, resulting in both improved spatial resolution and minimised sample charging and damage.

Figure 3. Field emission scanning electron microscope (FESEM) (JEOL JSM-7800F).

2.3.2. Energy Dispersive Spectroscopy (EDS)

Energy dispersive spectroscopy (EDS) works on chemical microanalysis methodology assisted with field emission scanning electron microscopy (FESEM). The characterization of the elemental composition of the analysed volume is performed by detecting X-rays emitted from the sample during bombardment by an electron beam. The electrons are ejected from the atoms after the bombardment of SEM's electron beam over sample. The energy difference between the two electrons' states is balanced by emitted X-ray. The electron vacancies are filled by electrons from a higher state. The relative abundance of emitted X-rays versus their power is measured by EDS X-ray detector. A charge pulse proportional to the energy of the X-ray is created by striking incident X-ray over a lithium-drifted silicon sensor. The charge-sensitive preamplifier converts charge pulse into a voltage pulse. The energy, as determined from the voltage measurement for each incident, causes an X-ray to be sent to a computer for display and further data evaluation.

3. Results

3.1. Physical Properties

3.1.1. Effect of Variety, Moisture Content, and Internode Position on Length in Wheat Crop

The effect of variety, moisture content, and internode position on length is presented in Table 2. The variety V2 had a higher length as compared to V1 at all levels of moisture content and internode position. The length was maximum at first internode and higher moisture content and decreased with internode position and decreased moisture content in both the varieties. It dropped from 33.96 cm at N1 to 6.28 cm at N5 in variety V1, and 36.80 cm at N1 to 8.62 cm at N5 in variety V2 as the straw moisture content decreased from 50% to 20%.

Table 2. Effect of variety, moisture content, and node position on the length of the wheat crop.

Variety		V1			V2		
Moisture Content (%) Internode	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**Overall Mean (N)**
N1	33.92	33.96	33.96	36.60	36.52	36.80	35.29
N2	20.54	20.52	20.58	23.78	23.92	24.22	22.26
N3	12.24	12.28	12.36	15.14	15.24	15.54	13.80
N4	10.22	10.14	10.10	12.30	12.40	12.56	11.29
N5	6.28	6.28	6.42	8.62	8.94	9.04	7.60
Overall mean (V)		16.65			19.44		
Overall mean (M)		17.96			18.02		18.16
CD (p = 0.05)	V = 0.28		MC = NS		IN = 0.44		V x MC x IN = NS

The overall length of V1 (16.65 cm) was significantly lower than V2 (19.44 cm). The average length decreased from 18.16 to 17.96 cm as the moisture content decreased from 50% to 20%, but the results were non-significant. The average length decreased significantly from 35.29 to 7.60 cm from the first internode to the fifth internode. The interaction between variety, straw moisture, and internode position for length is shown in Table 3.

Table 3. Interaction between variety, straw moisture, and internode position for length of wheat crop.

	M1	M2	M3		V1	V2		V1	V2
N1	35.26	35.24	35.38	N1	33.947	36.64	M1	16.64	19.288
N2	22.16	22.22	22.4	N2	20.547	23.973	M2	16.636	19.404
N3	13.69	13.76	13.95	N3	12.293	15.307	M3	16.684	19.632
N4	11.26	11.27	11.33	N4	10.153	12.42	-	-	-
N5	7.45	7.61	7.73	N5	6.327	8.867	-	-	-
Interaction		M x N = NS		Interaction	V x N = NS		Interaction	V x M = NS	

3.1.2. Effect of Variety, Moisture Content, and Internode Position on Stem Diameter of Wheat Crop

The effect of variety, moisture content, and internode position on stem diameter is presented in Table 4. The stem diameter of variety V1 was higher as compared to V2 at all levels of moisture content and internode position. The stem diameter was maximum at the fifth internode and higher moisture content, and decreased with internode position and decreased moisture content in both the varieties. It dropped from 4.86 cm at IN5 to 2.29 cm at N1 in variety V1, and 4.17 cm at N5 to 2.14 cm at N1 in variety V2 as the straw moisture content decreased from 50% to 20%.

Table 4. Effect of variety, moisture content, and node position on the stem diameter of the wheat crop.

Variety		V1			V2		
Moisture Content (%) Internode	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**Overall Mean (N)**
N1	2.29	2.52	2.87	2.14	2.33	2.54	2.45
N2	3.63	3.69	3.98	2.95	3.11	3.22	3.43
N3	3.72	3.95	4.38	3.31	3.35	3.59	3.72
N4	4.01	4.11	4.46	3.41	3.71	3.86	3.93
N5	4.15	4.57	4.86	3.36	3.97	4.17	4.18
Overall mean (V)		3.81			3.27		3.27
Overall mean (M)		3.30			3.53		3.79
CD (p = 0.05)	V = 0.18		M = 0.22		N = 0.29		V x M x N = NS

The overall stem diameter of V1 (3.81 cm) was significantly higher than V2 (3.27 cm). The average stem diameter decreased significantly from 3.79 to 3.30 cm as the moisture content decreased from 50% to 20%. The average stem diameter decreased significantly from 4.18 to 2.45 cm from the fifth internode to the first internode. Table 5 shows the interaction effect of variety, moisture content, and node position on diameter.

Table 5. Interaction between variety, straw moisture, and internode position for stem diameter of wheat crop.

	M1	M2	M3		V1	V2		V1	V2
N1	2.213	2.425	2.707	IN1	2.562	2.335	M1	3.560	3.035
N2	3.292	3.401	3.601	IN2	3.767	3.095	M2	3.769	3.293
N3	3.514	3.652	3.985	IN3	4.019	3.415	M3	4.112	3.477
N4	3.712	3.909	4.162	IN4	4.193	3.662	-	-	-
N5	3.756	4.269	4.517	IN5	4.527	3.834	-	-	-
Interaction		M x N = NS		Interaction	V x N = NS		Interaction	V x M = NS	

3.1.3. Effect of Variety, Moisture Content, and Internode Position on Stem Thickness of Wheat Crop

The effect of variety, moisture content, and internode position on stem thickness is presented in Table 6. The stem thickness of variety V1 was higher compared to V2 at all levels of moisture content and internode position. The stem thickness was maximum at fifth internode and higher moisture content and decreased with internode position and moisture content in both the varieties. It dropped from 0.58 mm at N5 to 0.38 mm at N1 in variety V1, and 0.42 mm at N5 to 0.33 mm at N1 in variety V2 as the straw moisture content decreased from 50% to 20%.

Table 6. Effect of variety, moisture content, and node position on stem thickness of wheat crop.

Variety		V1			V2		
Moisture Content (%) Internode	M1	M2	M3	M1	M2	M3	Overall Mean (N)
N1	0.38	0.38	0.39	0.33	0.34	0.36	0.36
N2	0.39	0.40	0.42	0.34	0.34	0.37	0.38
N3	0.48	0.42	0.44	0.34	0.35	0.38	0.40
N4	0.44	0.45	0.48	0.36	0.36	0.38	0.41
N5	0.50	0.55	0.58	0.36	0.37	0.42	0.46
Overall mean (V)		0.45			0.36		
Overall mean (M)		0.39			0.40		0.42
CD (p = 0.05)	V = 0.02		MC = 0.02		IN = 0.03		V x M x N = NA

The overall stem thickness of V1 (0.45 mm) was significantly higher than V2 (0.36 mm). The average stem thickness decreased considerably from 0.42 to 0.39 mm as the moisture content decreased from 50% to 20%. The average stem thickness significantly reduced from 0.46 to 0.36 mm from the fifth internode to the first internode. Table 7 shows the interaction between variety, straw moisture, and internode position for thickness.

Table 7. Interaction between variety, straw moisture, and internode position for stem thickness of wheat crop.

	M1	M2	M3		V1	V2		V1	V2
N1	0.352	0.36	0.373	N1	0.383	0.341	M1	0.435	0.346
N2	0.363	0.373	0.392	N2	0.402	0.35	M2	0.442	0.352
N3	0.411	0.386	0.413	N3	0.449	0.358	M3	0.462	0.382
N4	0.397	0.406	0.433	N4	0.458	0.366	-	-	-
N5	0.43	0.46	0.498	N5	0.541	0.385	-	-	-
Interaction		M x N = NS		Interaction	V x N = 0.04		Interaction	V x C = NS	

3.2. ANOVA for Physical Properties

The effect of variety and internode position on length was significant at the 5% level of significance (Table 8). The effect of moisture content and interactions of variables namely, variety-moisture content, variety-internode position, moisture content-internode position, and variety-moisture content-internode position, was non-significant (Table 8). The order of significance based on the *F*-values of these variables in descending order of the length was internode position, variety, and moisture content. The *F*-value for the internode position was the highest, indicating that it had a maximum effect on the length.

Table 8. ANOVA for effect of variety, moisture content, and node position on length of wheat crop.

Source of Variation	DF	Sum of Squares	Mean Squares	*F*-Calculated	Significance
Factor V	1	291.512	291.512	398.661	0.00001
Factor M	2	1.021	0.511	0.698	0.49946
Int V X M	2	0.544	0.272	0.372	0.69037
Factor N	4	14,644.05	3661.01	5006.66	0.00001
Int V X N	4	5.976	1.494	2.043	0.09263
Int M X N	8	0.19	0.024	0.032	0.99999
Int V X M X N	8	0.203	0.025	0.035	0.99998
Error	120	87.747	0.731		
Total	149	15,031.24			

The effect of variety, moisture content, and internode position on stem diameter was significant at the 5% level of significance (Table 9). The effect of interactions of variables namely, variety-moisture content, variety-internode position, moisture content-internode position, and variety–moisture content-internode position, was non-significant (Table 9). The order of significance based on the *F*-values of these variables in descending order of the length was internode position, variety, and moisture content. The *F*-value for the internode position was the highest, indicating that it had a maximum effect on the length.

Table 9. ANOVA for effect of variety, moisture content, and node position on stem diameter of wheat crop.

Source of Variation	DF	Sum of Squares	Mean Squares	*F*-Calculated	Significance
Factor V	1	11.157	11.157	35.716	0.00001
Factor M	2	6.182	3.091	9.895	0.00011
Int V X M	2	0.167	0.083	0.267	0.76641
Factor N	4	53.868	13.467	43.111	0.00001
Int V X N	4	1.07	0.268	0.856	0.49234
Int M X N	8	0.741	0.093	0.296	0.96595
Int V X M X N	8	0.206	0.026	0.083	0.99959
Error	120	37.486	0.312		
Total	149	110.876			

The effect of variety, moisture content, and internode position on stem thickness was significant at the 5% level of significance (Table 10). The effect of interactions of variables namely, variety–moisture content, moisture content–internode position, and variety–moisture content–internode position was non-significant (Table 10), but the interaction between variety and internode position was significant. The order of significance based on the *F*-values of these variables in descending order of length was variety, internode position, and moisture content. The *F*-value for the variety was the highest, indicating that it had maximum effect on the length.

Table 10. ANOVA for effect of variety, moisture content, and node position on stem thickness of wheat crop.

Source of Variation	DF	Sum of Squares	Mean Squares	*F*-Calculated	Significance
Factor V	1	0.281	0.281	90.356	0.00001
Factor M	2	0.027	0.014	4.369	0.01473
Int V X M	2	0.001	0	0.148	0.86252
Factor N	4	0.182	0.046	14.67	0.00001
Int V X N	4	0.06	0.015	4.856	0.00115
Int M X N	8	0.014	0.002	0.571	0.79969
Int V X M X C	8	0.01	0.001	0.398	0.91953
Error	120	0.373	0.003		
Total	149	0.949			

3.3. Mechanical Properties

The variation of tensile strength with respect to moisture percentage and successive nodes of the straw is shown in Figure 4. Figure 4a,b shows the variation of tensile strength for the varieties 1105 and 2967, respectively. The graph depicts that tensile strength of the straw increased with an increase in moisture. This was because the high moisture content increases the ductility of the straw. The more the ductility, higher the amount of absorbed energy will be until breaking occurs. As far as tensile strength variation among nodes is concerned, there was a steep increase in tensile strength from node 4 to node 5 in both the varieties. At a moisture content of 50% in variety 1105, the strength increased almost uniformly, but in the case of moisture content 20% and 30%, the variation was quite irregular. However, in variety HD-2967, except for node 1 to node 2 in the moisture content of 50%, all the levels showed an almost similar trend.

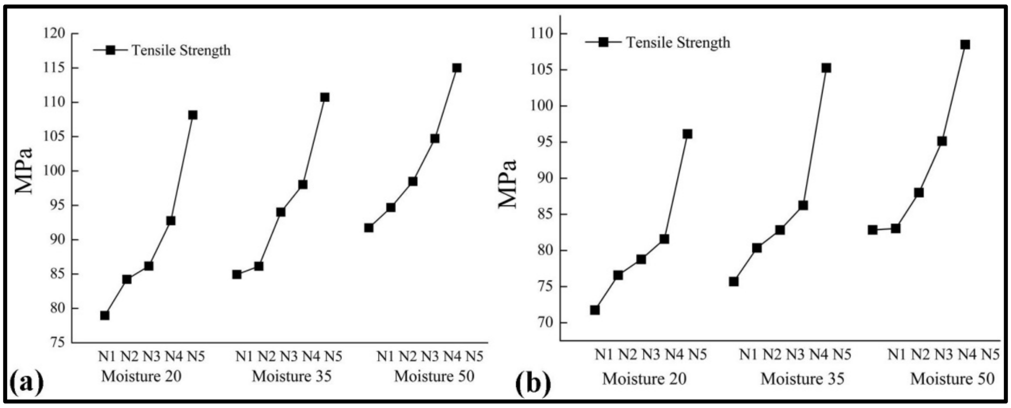

Figure 4. Variation in tensile strength with respect to moisture (%) and nodes in (**a**) variety WH-1105 and (**b**) variety HD-2967.

The variation of shear strength with respect to moisture percentage and successive nodes of the straw is shown in Figure 5. Figure 5a,b shows the variation of shear strength for the varieties WH-1105 and HD-2967, respectively. The graph depicts that shear strength of the straw decreased with an increase in the moisture. This was because the high moisture content decreases resistance to localised surface deformation.

As far as shear strength variation among nodes is concerned, there was a steep increase in shear strength from node 4 to node 5 in both varieties. At a moisture content of 20% in variety WH-1105, the graph shows the highest shear strength as compared to moisture content as well as variety HD-2967. The trend for variation in shear strength was similar for variety WH-1105, but in variety 2967, the trend at node 1 to 2 and node 3 to 4 showed a minimal increase in shear strength.

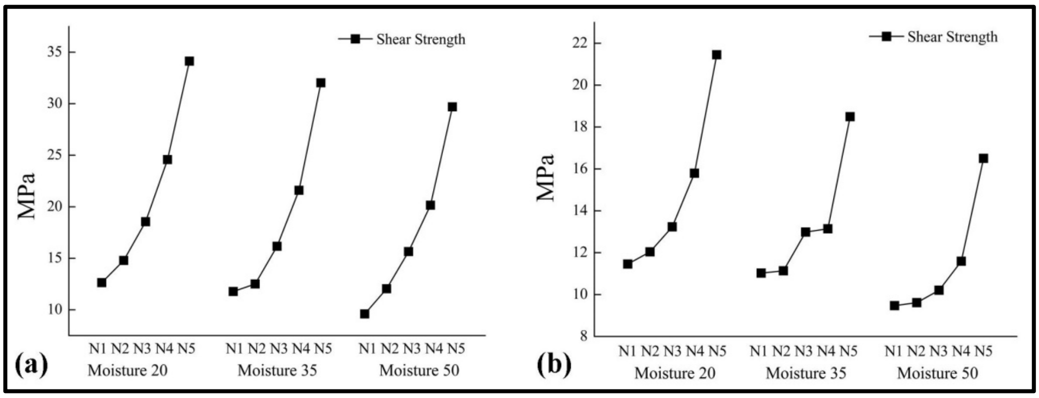

Figure 5. Variation in shear strength with respect to moisture (%) and nodes in (**a**) variety WH-1105 and (**b**) variety HD-2967.

The tabulated results for effect of variety, moisture content, and node position on tensile strength and shear strength on the wheat crop is shown in Tables 11 and 12, whereas the interaction between variety, straw moisture, and internode position for tensile strength and shear strength on the wheat crop is shown in Tables 13 and 14. The variety V2 had lower tensile strength as compared to V1 at all levels of moisture content and internode position. The tensile strength was minimum at first internode and more moderate moisture content, and increased with internode position and increased moisture content in both the varieties. It increased from 71.74 MPa at IN1 to 108.50 MPa at IN5 in variety V2, and 78.97 MPa at IN1 to 115.01 MPa at IN5 in variety V1 as the straw moisture content increased from 20% to 50%. The overall tensile strength of V2 (86.16 MPa) was significantly lower than V1 (95.25 MPa). The average tensile strength increased from 91.18 to 95.05 MPa as the moisture content increased from 20% to 50%. There was a significant difference concerning average tensile strength at the different moisture content of straw. The average tensile strength increased significantly from 80.99 to 107.30 MPa from the first internode to the fifth internode.

Table 11. Effect of variety, moisture content, and node position on tensile strength of wheat crop.

Variety	**V1**			**V2**			
Moisture Content (%) Internode	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**Overall Mean (N)**
N1	78.97	84.95	91.74	71.74	75.68	82.84	80.99
N2	84.23	86.14	94.68	76.58	80.35	83.05	84.17
N3	86.17	94.02	98.48	78.77	82.84	88.01	88.05
N4	92.76	98.03	104.73	81.58	86.25	95.14	93.08
N5	108.15	110.74	115.01	96.13	105.28	108.50	107.30
Overall mean (V)		95.25			86.18		
Overall mean (M)		91.18			92.46		95.05
CD ($p = 0.05$)	V = 0.94		MC = 1.15		IN = 1.48		V x MC x IN = 3.63

The effect of variety, moisture content, and internode position on shear strength is presented in Table 12. The variety V2 had lower tensile strength compared to V1 at all levels of moisture content and internode position. The shear strength was minimum at the first internode and higher moisture content and increased with internode position and decreased moisture content in both the varieties. It increased from 9.47 MPa at N1 to 21.45 MPa at IN5 in variety V2, and 9.60 MPa at N1 to 34.13 MPa at N5 in variety V1 as the straw moisture content decreased from 50% to 20%.

The overall shear strength of V2 (13.21 MPa) was significantly lower than V1 (19.06 MPa). The average shear strength decreased from 19.32 to 14.45 MPa as the moisture content increased from 20% to 50%. There was a significant difference concerning average shear strength at a different moisture content of straw. The average shear strength increased significantly from 11 to 25.39 MPa from the first internode to the fifth internode.

Table 12. Effect of variety, moisture content, and node position on shear strength of wheat crop.

Variety	V1			V2			
Moisture Content (%) Internode	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**Overall Mean (N)**
N1	12.64	11.776	9.596	11.458	11.028	9.472	11.00
N2	14.788	12.508	12.044	12.042	11.136	9.616	12.02
N3	18.548	16.162	15.652	13.234	12.984	10.206	14.46
N4	24.576	21.598	20.154	15.792	13.142	11.594	17.81
N5	34.132	32.032	29.698	21.452	18.494	16.504	25.39
Overall mean (V)		19.06			13.21		
Overall mean (M)		19.32			17.26		14.45
CD (p = 0.05)	V = 0.40		MC = 0.49		IN = 0.63		V x MC x IN = NS

Table 13. Interaction between variety, straw moisture, and internode position for tensile strength of wheat crop.

	M1	M2	M3		V1	V2		V1	V2
N1	75.358	80.315	87.29	N1	85.219	76.756	M1	90.057	80.961
N2	80.406	83.248	88.866	N2	88.352	79.995	M2	94.774	86.081
N3	82.471	88.427	93.247	N3	92.89	83.207	M3	100.928	91.509
N4	87.17	92.139	99.934	N4	98.505	87.657	-	-	-
N5	102.141	108.009	111.757	N5	111.3	103.305	-	-	-
Interaction		MC x N = NS		Interaction	V x N = NS		Interaction	V x MC = NS	

Table 14. Interaction between variety, straw moisture, and internode position for shear strength on wheat crop.

	M1	M2	M3		V1	V2		V1	V2
N1	12.049	11.402	9.534	N1	11.337	10.653	M1	20.937	14.796
N2	13.415	11.822	10.83	N2	13.113	10.931	M2	18.815	13.357
N3	15.891	14.573	12.929	N3	16.787	12.141	M3	17.429	11.478
N4	20.184	17.37	15.874	N4	22.109	13.509	-	-	-
N5	27.792	25.263	23.101	N5	31.954	18.817	-	-	-
Interaction		M x N = 1.09		Interaction	V x N = 0.89		Interaction	V x M = NS	

3.4. ANOVA for Mechanical Properties

The effect of variety, moisture content, and internode position on tensile strength was significant at the 5% level of significance (Table 15). The effect of interactions of variables, namely, variety–moisture content, variety–internode position, and moisture content–internode position, was non-significant (Table 15), but the interaction of variety–moisture content-internode position was significant. The order of significance based on the *F*-values of these variables in descending order of tensile strength was internode position, variety, and moisture content. The *F*-value for the internode position was the highest, indicating that it had a maximum effect on tensile strength.

The effect of variety, moisture content, and internode position on shear strength was significant at the 5% level of significance (Table 16). The effect of interactions of variables namely, variety–internode position and moisture content–internode position, was significant (Table 16), but the interaction of variety–moisture content and variety-moisture content-internode position was non-significant. The order of significance based on the *F*-values of these variables in descending order of tensile strength was variety, internode position, and moisture content. The *F*-value for the variety was the highest, indicating that it had a maximum effect on the shear strength.

Table 15. ANOVA for effect of variety, moisture content, and node position on tensile strength of wheat crop.

Source of Variation	DF	Sum of Squares	Mean Squares	*F*-Calculated	Significance
Factor V	1	3084.58	3084.58	366.91	0.00
Factor M	2	2873.65	1436.82	170.91	0.00
Int V X B	2	3.39	1.69	0.20	0.82
Factor N	4	12,757.88	3189.47	379.39	0.00
Int V X N	4	41.85	10.46	1.24	0.30
Int M X N	8	96.18	12.02	1.43	0.19
Int V X M X N	8	135.82M	16.98	2.02	0.05
Error	120	1008.83	8.41		
Total	149	20,002.17			

Table 16. ANOVA for effect of variety, moisture content, and node position on shear strength of wheat crop.

Source of Variation	DF	Sum of Squares	Mean Squares	*F*-Value	Significance
Factor V	1	1283.32	1283.32	843.735	0.00001
Factor M	2	291.304	145.652	95.761	0.00001
Int V X M	2	3.126	1.563	1.028	0.36101
Factor N	4	4034.88	1008.72	663.196	0.00001
Int V X N	4	766.915	191.729	126.054	0.00001
Int M X N	8	26.89	3.361	2.21	0.03120
Int V X M X N	8	10.051	1.256	0.826	0.58126
Error	120	182.52	1.521		
Total	149	6599.01			

3.5. Field Emission Scanning Electron Microscopy

The morphological analysis for the wheat straw WH-1105 and HD-2967 was analysed using FESEM for the availability of the moisture content. The observed images, as shown in Figures 6 and 7, indicate that the moisture was mostly present in the inner layer of the straw. The outer layer of the straw showed the absence of moisture, which meant that the straw showed dual behaviour during the harvesting process. The outer layer of the straw showed brittle fracture, whereas, due to presence of moisture over the inner layer, the elasticity of the straw increased. This increase in elasticity turned brittle fracture behaviour into ductile fracture.

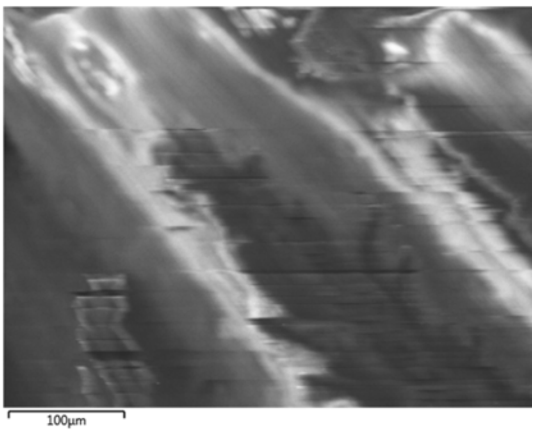

Figure 6. Field emission scanning electron microscopy (FESEM) image of wheat straw WH-1105.

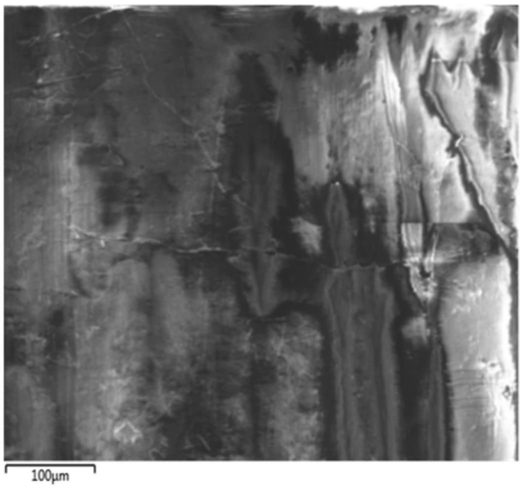

Figure 7. FESEM image of wheat straw HD-2967.

3.6. Energy Dispersive Spectroscopy and Mapping Analysis

The presence of various elements such as carbon, oxygen, silica, iron, and potassium was confirmed by the energy dispersive spectroscopy (EDS) results shown in Figure 8. The EDS mapping analysis showed the spatial distribution of elements present in the straw. Different colour maps showed the presence of variable elements over the same area. In the present straw, the carbon and iron were chief constituents that were also validated by mapping analysis, as shown in Figure 9. The presence of silicon in the variety of WH-1105 provided a strong reason for better mechanical properties as compared to variety HD-2967. The EDS of wheat variety as shown in Figure 10 confirmed the presence of carbon and oxygen as key elements. The mapping analysis for identification of these elements is validated in Figure 11.

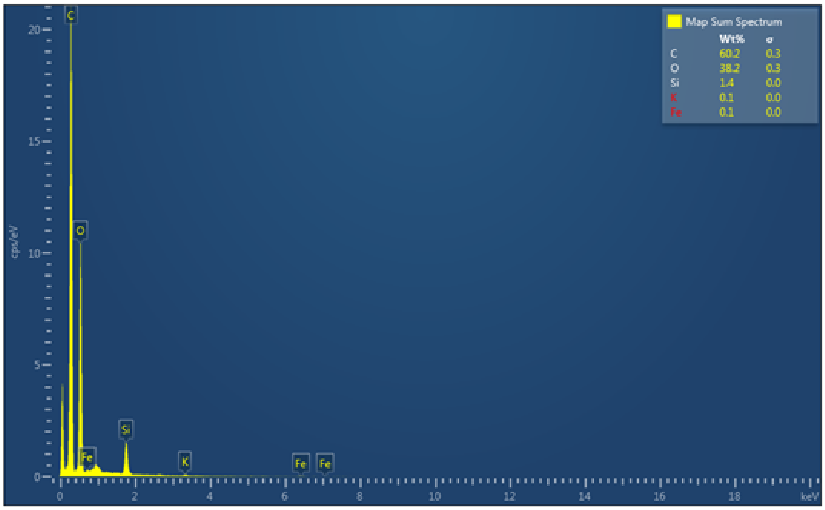

Figure 8. Energy dispersive spectroscopy of wheat straw WH-1105.

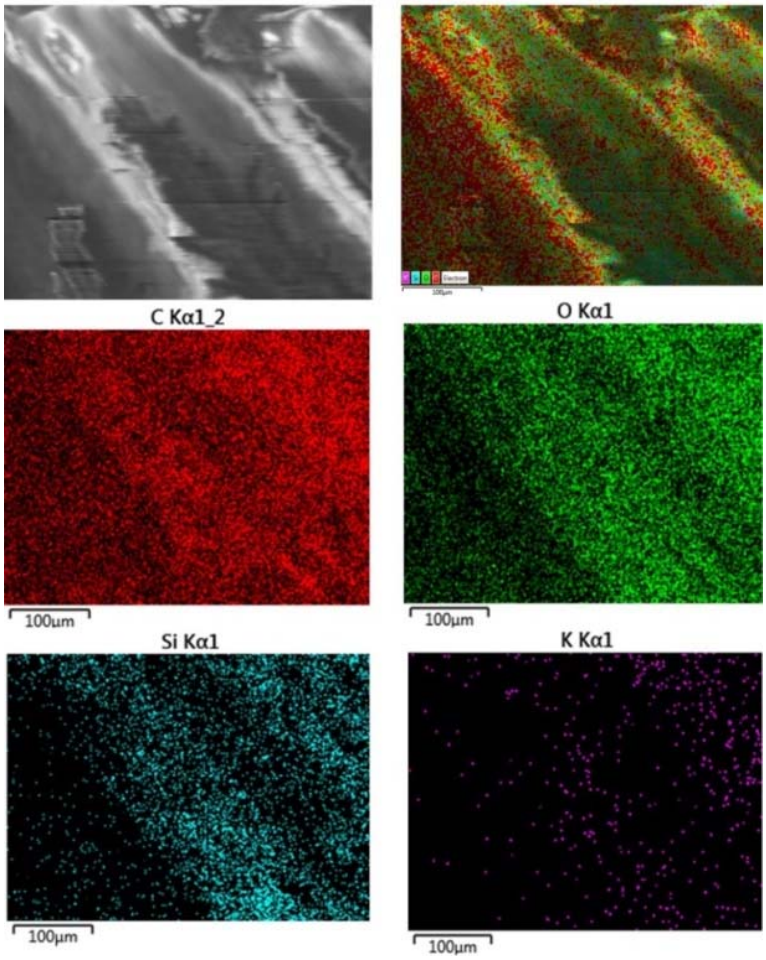

Figure 9. Mapping analysis of elements in wheat straw WH-1105.

Figure 10. Energy dispersive spectroscopy of wheat straw HD-2967.

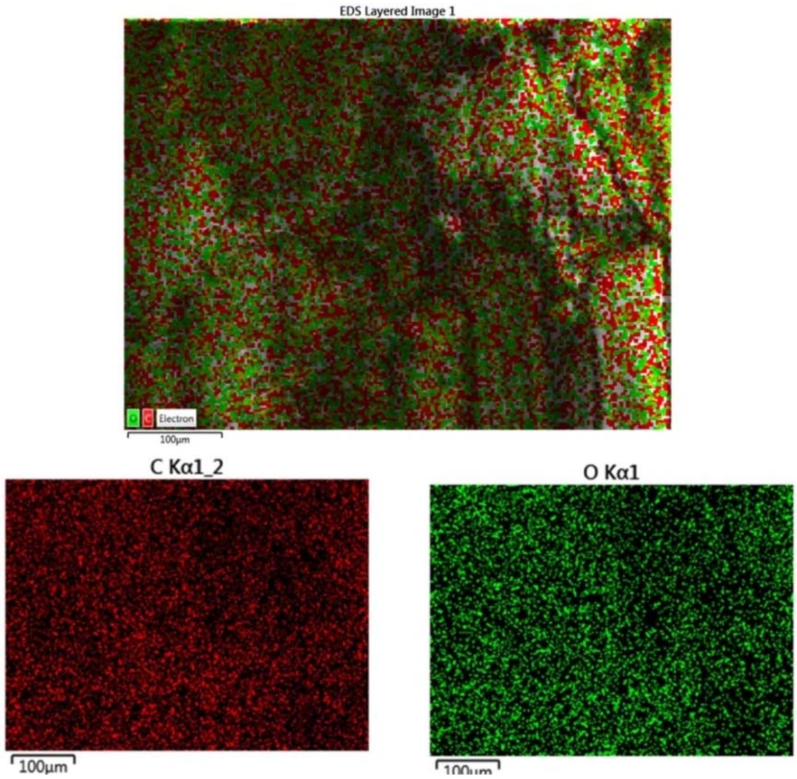

Figure 11. Mapping analysis of elements in wheat straw HD-2967.

4. Discussions

The physical characterization on the wheat crop was conducted on the basis of length, stem diameter, and stem thickness criterion at variable nodes and moisture content. The results showed that length of the nodes decreased from the node 1 to node 5 in both the varieties, but individually HD-2967 had longer node length than WH-1105. For the stem diameter and stem thickness, the available trend showed that both the parameters increased from the node 1 to node 5 in both the varieties, but comparative analysis of the varieties showed that WH 1105 had more stem diameter and stem thickness than HD-2967. Supportive observation regarding node length and stem thickness was also reported by Nazari et al. [44]. The comparative analysis of moisture content showed that shear strength in varieties WH-1105 and HD-2967 decreased with increase in moisture content, whereas the tensile strength increased with increase in moisture content in both the varieties. The key reason behind this trend was the increase in ductility of the straws. The straw having comparatively low moisture content exhibited a brittle deformation phenomenon, which turned towards ductile with increase in moisture content. Li et al. [50] observed that shear resistance decreased with an increase in the moisture content in the grain, whereas deformation increased with the increase of moisture content. Similar results were also available for stalk, where the cutting force in dry stalk decreased with increase in moisture because the ratio of material per unit area was higher than the high moisture content [51]. In addition, the morphological analysis showed that WH 1105 had carbon content of 56.6%, whereas HD-2967 had carbon content of 55.6%. It was evident that the higher content of carbon increased yield stress and ultimate tensile stress [52]. The higher percentage of the carbon also increased the resistance to deformation, which makes WH-1105 harder to cut as compared to HD-2967.

5. Conclusions

On the basis of the present experimental study, the following conclusions can be drawn:

- The tensile and shear strength of wheat variety WH-1105 and HD-2967 was evaluated, and it was concluded that wheat variety WH-1105 was superior in terms of tensile and shear strength compared with wheat variety HD-2967. In the comparison of the nodes, the tensile and shear strength at node 5 (lower most node) of straw possessed higher tensile as well as shear strength.

- The ANOVA for physical properties showed that moisture content was directly proportional to the stem diameter and stem thickness, whereas moisture content had no relation with the length of the stem.
- The ANOVA for mechanical properties showed that moisture content significantly affected tensile strength as well as the shear strength. The result showed moisture was directly proportional to the tensile strength and inversely proportional to the shear strength.
- The morphological analysis of the straws confirmed the presence of moisture content in the straw.
- The energy dispersive spectroscopy (EDS) provided information regarding the presence of constituting elements in the straw. The mapping analysis of the straw delivered the exact location of forming elements.
- The EDS confirmed the presence of silicon in the wheat variety WH-1105, which was the primary reason for its better strength as compared to wheat HD-2967. The presence of silicon improved tensile, shear, as well as yield strength, which makes it harder to harvest as compared with wheat HD-2967.

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