



3D Color Grading Approach for Wool Using Visual and Instrumental Analysis in Multiple Color Spaces: A Modern Perspective on Wool Color Grading

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Abstract

The accurate color grading of wool plays a pivotal role in determining the quality and performance of the resultant yarn and fabrics, and it is considered a key parameter in international wool trade. Conventionally, wool fibers are being assessed visually by trained classers, supported by the instrumental measurements based on conventional color attributes such as Y (brightness) and Y–Z (yellowness). However, these limited attributes do not represent discoloration, dark fibers, and trash content, often resulting in the discrepancies between visual and instrumental grading systems. Our research work proposes an improved and comprehensive approach to wool color grading as it incorporates multiple colors spaces and illuminants to represent color in a three-dimensional (3D) model that aligns more closely with human visual perception. Additionally, the effects of geometrical configurations and light sources on instrumental color measurements are also investigated. For wool color grading appropriate for international trade, the suggested system provides a more precise, dependable, and consistent approach by bridging the gap between subjective visual judgment and objective instrumental assessment.

Keywords Wool grading · Tristimulus · Color spaces · Advanced color grading · D65 illuminant

1 Introduction

Wool is a natural fiber with significant importance in the global textile industry, especially in the countries that dominate its production. A thorough grading procedure based on a number of physical characteristics, such as fiber length, strength, fineness, uniformity, and color, determines the quality of wool and, consequently, its worth in international trade [1–3]. Among these factors, color grading plays a pivotal role in quality of wool, because discoloration is often associated with inferior quality and reduced performance in

dyeing and wool fabric esthetics [4, 5]. The discoloration of wool leads to some major drawbacks, like tenderness and wool degradation [5].

Despite technological advancements, color grading of wool continues to rely heavily on subjective visual assessment performed by trained classers, especially in major wool-producing regions. Visual grading is traditionally supported by instrumental methods, which quantify wool color based on attributes such as Y (brightness) and Y–Z (yellowness) [6, 7]. However, these parameters do not fully capture other important features such as discoloration, the presence of dark fibers, and trash content, leading to inconsistencies between visual and instrumental assessments [8].

Yellowness in wool, a major fault in grading, can result from environmental conditions, late shearing, moisture, or contamination from urine. Early shearing, preferably in early spring, is often recommended to minimize this issue [9]. Unfortunately, the attributes of wool color measurements do not represent these dark fibers, and ultimately, these fibers contribute to the overall color grade of wool. Additionally, wool may contain naturally pigmented or stained fibers, known as dark fibers, which often originate from black sheep within a predominantly white flock [10]. Although these

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fibers are few in number, they significantly impact visual perception and market value. For instance, a concentration exceeding 20 dark fibers per 100 g of wool may result in price deductions [11].

Visual color assessment of wool fibers and other natural fibers is always controversial due to the disagreement of the instrumental and visual color assessment. The major reason for this disagreement is the representation of the color in the relevant color spaces. Human vision system uses Hue and Chroma in describing the color while most of the instrumental color assessments are based on old attributes which are not close to human vision system [9, 12, 13]. The light source and the background are also very important factors in describing the color for its precise measurement. Normally, D65 is used as the light source in the wool color grading as it represents the daylight temperature and black background is also used for the assessment. In this research, these two issues will be addressed as the color represented in the LCH color space which is closer to the human vision system. And the different backgrounds will be used to optimize the effect background on the color measurement.

The storage of wool also influences the wool color. Greasy wool stored for a period of 6–12 months may leads to yellowish, reducing its physical and mechanical characteristics, including absorbance, dyeability, and tensile strength. On the contrary, wool produced in dry areas tends to retain its whiteness and brightness, earning it higher color grades and market value [14, 15]. Most common source of wool discoloration is diffuse yellowness, and this term refers to the sheep which used to live in moist and warm conditions and the wool is sheer late in these areas. This discoloration is scorable but still it affects the actual raw wool color. Some of the discoloration of wool fibers are not very dangerous for the fiber structure but the color discoloration which developed due to the bacterial action can damage the fiber structure and the quality of the wool will be less [16].

Wool color is represented through its conventionally used attributes which are no longer compatible if compared with the recent color spaces and the wool color is not truly represented as the third attribute is not used for the representation. These two-dimensional measures overlook the full range of color attributes, including hue and chroma, which are essential for a comprehensive color evaluation [17, 18]. Moreover, the geometrical design and illuminant settings of color measurement devices can further affect the consistency of instrumental results, especially when compared to human visual assessment.

To address these limitations, the present study explores a novel three-dimensional (3D) color grading approach using advanced color spaces under multiple illuminants. By incorporating all three attributes of color and employing spaces that closely mimic human vision, the present research work aims to bridge the gap between visual and instrumental

methods. To the best of our knowledge, this is the first detailed investigation of wool color grading using 3D color spaces for a more precise, reliable, and internationally relevant assessment. This modernized approach has potential for minimizing disagreement between classer-based and instrument-based grading, thereby improving accuracy and transparency in wool quality evaluation.

Main objectives of the study include developing the 3D color space method to represent the wool color in that framework and to add a modern tool for precise wool color assessment. And the most important part is to use different color spaces for color representation which offer more reliable and compatible color values in the present era. This new version of the color analysis techniques will be highly adaptable and trustworthy in the wool color analysis. It is also shown in the study that spectral data base color measurement is very important to obtain the color assessment close to human vision system. This will reduce the discrepancy between the different color measurement methods used.

2 Materials and Methods

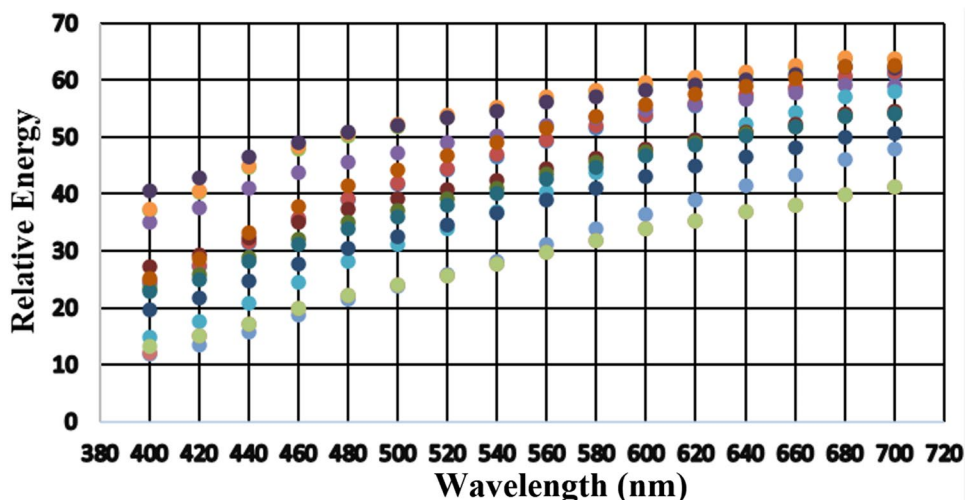
A total of 25 wool samples were collected from the northern regions of Pakistan (Skardu and Gilgit). Each sample weighed 20 g. Prior to testing their color appearance, the samples were conditioned in the Fiber Testing Laboratory, Department of Fiber and Textile Technology, University of Agriculture, Faisalabad, for 8 h to achieve moisture regain. Professionally trained groups of people were involved in this research to visually grade the wool fiber according to the international standards. These people were of different age groups to ensure the quality of the visual grading process of wool. The visual grading of wool involves the measurement of brightness (Y) and the measurement of yellowness (Y–Z), and the measurement of the same attributes with the instrumental measurement to relate them at the same color temperature. The wool samples contained trash content and dark fibers, which deteriorate the quality of wool. The wool color grader made sure that while grading the wool, the trash contents were not taken into consideration, and the assigned grade was purely based on wool fibers.

The attributes used to describe the color of wool, namely (Y) and (Y–Z), are outdated compared to the color spaces available today. The spectral data of the wool samples are measured to determine the precise and accurate color measurement as shown in Fig. 1. The spectral data measured color closer to the human vision system as it measures values in the visible region from (400–700) nm as shown in Fig. 2. Tristimulus values (XYZ) are also measured of the wool samples at D65 illuminant as these values will be used for the comparison of visual data and CIE Lab color space. The color space CIE xyY is also used

Fig. 1 Color measurement of wool samples with a spectrophotometer



Fig. 2 Spectral data of the wool samples measured with a spectrophotometer



here to represent the color of wool samples to compare it with other color spaces and visual classification. The values are obtained on D65 and F11 illuminants to visualize the brightness and yellowness values and compare them with the visual measurement [19].

The professional wool classer is used in this research to describe the color of wool for its more precise grading purpose. These visual classers are very aware of the wool grading process used globally, and they have been professionally trained for wool grading for the past 15 years. The visual grading of wool samples took place under Illuminant D65 and F11 with a black background. Three professionally trained observers measure the color grade of wool samples, and the comparison between brightness and yellowness is studied to represent the color of wool samples in a new color space. The representation of the color of wool samples will enhance the possibility of reducing the disagreement between the instrumental and visual color values and predicting the wool color grades more accurately. The Miniscan and Labscan are also used to determine the impact of geometrical construction on the color value of wool samples [20].

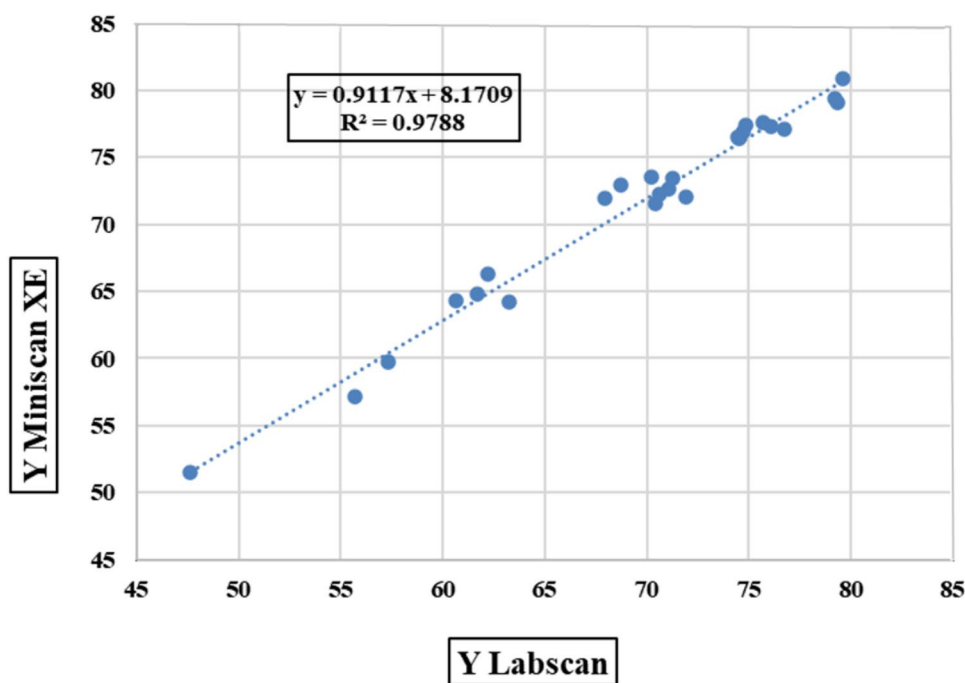
3 Results and Discussion

3.1 Comparison of the Y Values (Wool Samples) between Miniscan Xe and Labscan

To verify that sometimes the instruments measure the same parameters, but the geometry utilized for measurement is different and impacts the parameters, the Miniscan XE and Labscan are compared. The Hunterlab Miniscan and Labscan are no different. These two devices appear to have the same appearance and measure the same parameters, but the Miniscan XE has 45°-0° geometry and the Labscan has 0°-45° geometry. The values derived from these two instruments clearly show the influence. This is caused by the sample's exposure to light and the variation in refractive indices [21].

The Y results from Labscan are lower than the Y values from Miniscan XE in Fig. 3. Here, the Y values correspond to the Rd values. One of the main causes of varying Rd (Y) values is the geometry of the instrument, where the angle of the incident light source differs from that of

Fig. 3 Comparison of wool samples: brightness values (Y) between Labscan and Miniscan XE



the other instrument. The Rd values are dependent on the incident angle of the light source [22]. By using the optical indicatrix, the maximum and minimum refractive indices of a section through a mineral can be used to calculate the refractive indexes of that section. The directions of the maximum and minimum refractive indices indicate the vibration directions of the light beam traveling perpendicular to this portion. The rapid and slow rays are the names given to these directions.

3.2 Color Measurement of Wool Fibers in Different Color Spaces

Table 1 represents the color values of wool samples measured under the same illuminant D65 with the same conditions. Here, the brightness (Y) value with tristimulus (CIE XYZ) and CIE xyY is the same, but the lightness value with CIE LAB is higher under the same illuminant, which shows a higher trend of the lightness value. These higher values of L (Lightness) will always be seen in comparison with the Rd (Degree of reflectance) and Y (Brightness) values [23]. Table 2 represents the color difference (ΔE) for the CIEDE2000 or CIE LAB. This gives more statistical comprehensive reviews of the data for the precise color evaluation. By using the statistical software, Trilobyte QC expert, the observations were analyzed with the given results. Table 3 summarizes the analysis of variance (ANOVA) of the L^* , a^* , and b^* values for the CIE Lab. It can be seen from Table 3 that all the attributes of color are significant in the plot of means under different illuminants.

Figure 4 and Fig. 5 show the Y (brightness) value and the yellowness (Y–Z) values of the wool samples measured in CIE LAB color space, respectively. This measurement does not indicate the discoloration or trash content present on the surface of wool fiber and gives an average color of the surface of the wool sample. Y–Z yellowness values show the discoloration of the sample and indicate the color deterioration of the sample [24]. Normally, the color is represented in three attributes in CIELAB system where ‘L’ stands for lightness and darkness, ‘a’ stands for redness/greenness, and ‘b’ stands for yellowness/blueness, but in case of wool fiber, the color is represented in two co-ordinates and the ‘a’ which represents redness/greenness is ignored as the wool fibers possess very negligible value of ‘a’ as shown in table. This negligible value of ‘a’ does not contribute to the grading system of wool samples, but possesses a considerable value in the case of wool samples [25].

3.3 Visual Assessment of Wool Samples for the Comparison of Brightness (Y) and Yellowness (Y–Z) Values

The visual color grading system is used in the natural fiber industry even though there are numerous advanced color measurement devices in the industry. The instrumental color measurement system is still not very reliable in this industry for assigning the final grade due to the color variation in the natural fibers. To represent the color of raw wool fibers, it is very important that the color described through the instrument should be in the same manner as the visual color measurement [26]. Figures 6 and 7, respectively, describe the

Table 1 Representation of samples of wool fibers in different color spaces CIE LAB, CIE XYZ, and CIE xyY with illuminant D65

Wool Samples	D65			D65			D65		
	L^*	a^*	b^*	X	Y	Z	x	y	Y
1	74.71	2.42	17.2	46.3	47.82	36.71	0.35	0.37	47.82
2	74.88	2.42	17.14	46.56	48.09	36.99	0.35	0.36	48.09
3	79.37	0.93	9.71	53.18	55.57	50.41	0.33	0.35	55.57
4	76.75	1.33	9.6	49.07	51.12	46.22	0.34	0.35	51.12
5	68.72	5.45	23.27	38.71	38.96	25.2	0.38	0.38	38.96
6	79.62	0.86	9.77	53.57	56.01	50.77	0.33	0.35	56.01
7	67.93	3.28	16.28	36.99	37.88	28.83	0.36	0.37	37.88
8	71.91	2.43	12.21	42.17	43.53	36.84	0.34	0.36	43.53
9	71.09	2.72	15.09	41.1	42.32	33.54	0.35	0.36	42.32
10	79.2	0.95	7.87	52.09	55.28	51.94	0.33	0.35	55.28
11	70.45	3.14	15.28	40.35	41.39	40.45	0.35	0.36	41.39
12	76.12	1.8	16.83	48.25	50.08	38.97	0.35	0.36	50.08
13	61.67	6	21.82	30.02	30.09	19.17	0.38	0.38	30.02
14	62.2	5.26	21.04	30.5	30.64	20.05	0.38	0.38	30.64
15	60.63	4.01	17.62	28.41	28.83	20.43	0.37	0.37	28.83
16	57.34	6.18	21.28	25.46	25.27	15.83	0.38	0.38	25.27
17	55.73	7.78	24.82	24.21	23.64	13.15	0.4	0.39	23.64
18	75.69	1.61	12.91	47.51	49.38	41.64	0.34	0.36	49.38
19	71.24	2.09	11.23	41.11	42.54	36.7	0.34	0.35	42.54
20	74.49	1.18	11.46	45.53	47.47	41.11	0.34	0.35	42.54
21	74.5	1.7	12.19	45.73	47.49	40.51	0.34	0.36	47.49
22	70.21	2.76	15.59	39.89	41.05	32.05	0.35	0.36	41.05
23	63.23	4.82	19.02	31.59	31.86	22.13	0.37	0.37	31.86
24	70.62	2.62	13.95	40.41	41.64	33.78	0.35	0.36	41.64
25	47.64	8.56	22.58	17.21	16.51	9.01	0.4	0.39	16.79

two-color parameters of wool fibers under D65 illuminant. These visual observations are performed by three professionally trained wool color classers who are aware of the natural fiber color grading process [27]. Figures show that the visual classer assigns the same final color grade to wool fibers based on their brightness (Y) and yellowness (Y–Z) values. The visual classers do not take into consideration the trash particles present on the surface of fibers [28].

3.4 Comparison of (Y) and (Y–Z) Values between CIED65 and the Observers' Measurements

The spectral data between 400 and 700 nm are used here to obtain the brightness value of the wool samples. It is widely believed that the values obtained from the spectra data are closer to the human vision system. In Figs. 8 and 9, the brightness and yellowness values of wool samples are graphically represented between visual observation values and data obtained from the spectral data.

A strong correlation is found between the CIE spectral data values and visual observer data. The illuminant used for this data is D65, as it represents daylight, and mostly

the natural fibers are graded under D65 for their final color grade. It can also be seen in Fig. 9 that the correlation for yellowness is not as strong as it is in the case of brightness. The reason behind this weak relation is that the observers do not take into consideration the dark particles on the sample surface as wool, while the spectral data take these dark particles into color measurement [24, 29]. Table 4 shows the R^2 values of brightness and yellowness under D65 illuminants. It is obvious from the results that the values obtained by the CIE spectral data showing strong correlation with the visual observer data in the D65 illuminant [30]. Similarly, the y-intercept and slope can also be observed in the results that show strong relationship between two data sets and neglecting disagreement between visual and instrumental measurements.

3.5 Representation of Wool Color in CIE xyY Color Space

The wool color of the samples is represented in the CIE xyY color space to see the presentation of wool color in a different color spaces. The CIE xyY color space is not used to represent the color of natural fibers, but the color representation

Table 2 Color differences (ΔE) is calculated according to the CIEDE2000 or CIELAB system

L^*	a^*	b^*	L^*	a^*	b^*	ΔE^* (CIE Lab)	ΔE (CIEDE2000)
74.71	2.42	17.2	73.58	3	12.68	4.70	3.45
74.88	2.42	17.14	74.35	3	11.84	5.36	4.11
79.37	0.93	9.71	77.38	1.51	8.34	2.48	1.23
76.75	1.33	9.6	76.38	1.91	8.61	1.21	0.92
68.72	5.45	23.27	69.32	6.03	10.84	12.46	11.21
79.62	0.86	9.77	78.33	1.44	9.29	1.49	0.24
67.93	3.28	16.28	69.37	3.86	14.92	2.06	0.81
71.91	2.43	12.21	71.19	3.01	9.86	2.53	1.28
71.09	2.72	15.09	71.17	3.3	13.78	1.43	0.18
79.2	0.95	7.87	79.35	1.53	9.15	1.41	0.16
70.45	3.14	15.28	71.54	3.72	12.75	2.82	1.57
76.12	1.8	16.83	76.21	2.38	16.97	0.60	0.35
61.67	6	21.82	61.76	6.58	16.78	5.07	3.82
62.2	5.26	21.04	62.31	5.84	12.89	8.17	6.92
60.63	4.01	17.62	60.53	4.59	14.81	2.87	1.62
57.34	6.18	21.28	57.43	6.76	14.47	6.84	5.59
55.73	7.78	24.82	55.37	8.36	16.61	8.24	6.99
75.69	1.61	12.91	76.96	2.19	17.24	4.55	3.30
71.24	2.09	11.23	71.42	2.67	16.74	5.54	4.29
74.49	1.18	11.46	74.94	1.76	16.43	5.02	3.77
74.5	1.7	12.19	75.05	2.28	13.47	1.51	0.26
70.21	2.76	15.59	69.12	3.34	19.31	3.92	2.67
63.23	4.82	19.02	65.32	5.4	16.45	3.36	2.11
70.62	2.62	13.95	70.2	3.2	14.67	1.02	0.68
47.64	8.56	22.58	50.49	9.14	14.18	8.89	7.64

Table 3 Anova table for $L^*a^*b^*$ values under different illuminants

Source of variability	Sum of squares	Mean squares	Degree of freedom	Standard deviation	F-statistic	Critical quartile	Conclusion	p-value
b^*	18.87	9.44	2	3.07	2.35	2.98	Significant	.03
L^*	705.67	64.15	11	8.01	2.42	2.30	Significant	.04
a^*	5.82	5.82	1	24.13	1.21	2.65	Significant	.03
Residuals	576.35	27.45	21	5.24				
Total	1306.71	37.33	35	6.11				

in this color space is that it separates the chroma from the brightness (Luminance). It gives the opportunity to obtain the true color attributes, which are not device-dependent. The influence of color measurement device is not affecting the true color of the sample inside the color representation. The CIE xyY color space: Figure 10 is normally derived from the CIE XYZ values. So, one of the main advantages of representing the color in this color space is that it ensures consistent color representation in all viewing conditions. The x and y co-ordinates describe the color hue and saturation, which are perceived as true color, and Y represents the brightness [27, 31].

3.6 Representation of Wool Color in 3D Color Spaces

The representation of wool color by using all three-color attributes has now become a major need for the natural fiber grading process. In color science, the true representation of color is only possible when all the attributes are involved in the color presentation Fig. 11 and Fig. 12. Unfortunately, in the natural fiber grading process, only two attributes are considered as responsible for the final decisions. The third attribute shows negligible values, and it does not contribute to the color grading process effectively [28]. So, if the third attribute is removed, then the color will not be affected. In

Fig. 4 The brightness (Y) value of wool samples measured with D65 illuminant

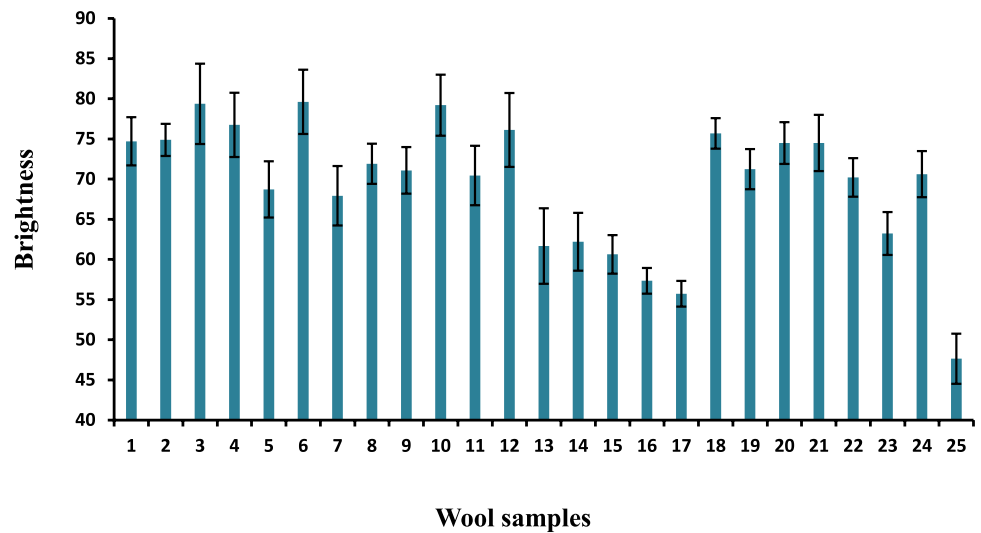


Fig. 5 The yellowness (Y-Z) value of wool samples measured with D65 illuminant

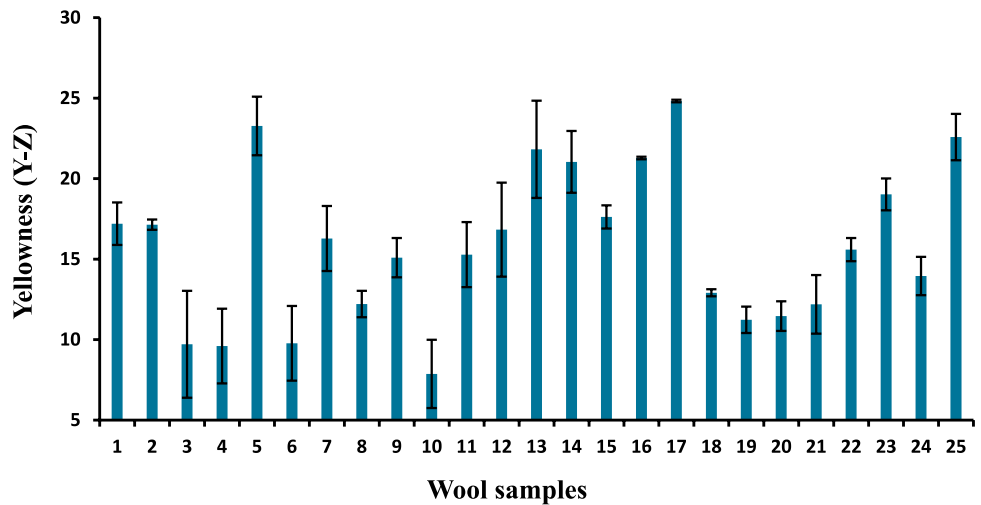


Fig. 6 The representation of wool brightness (Y) by using different visual observations

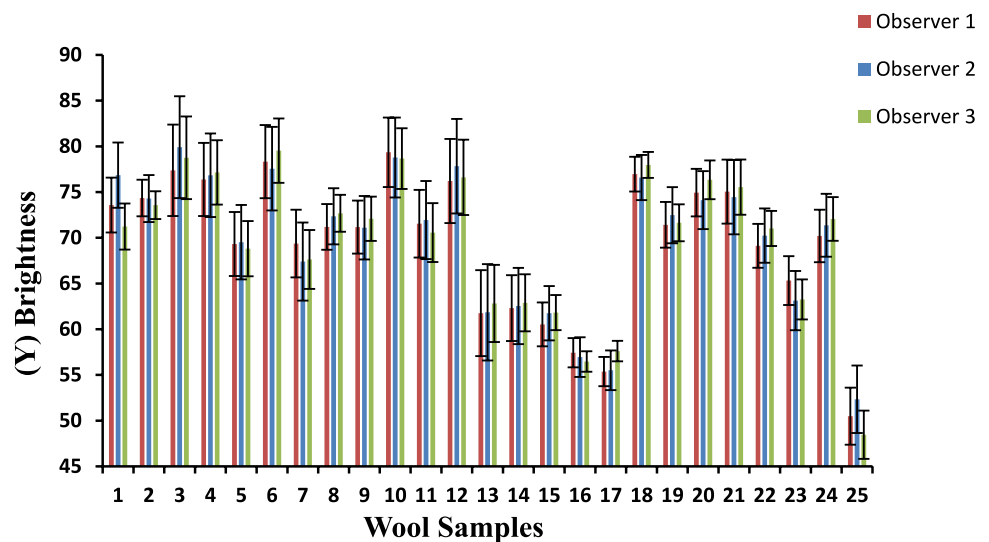


Fig. 7 The representation of wool yellowness (Y–Z) by using different visual observations

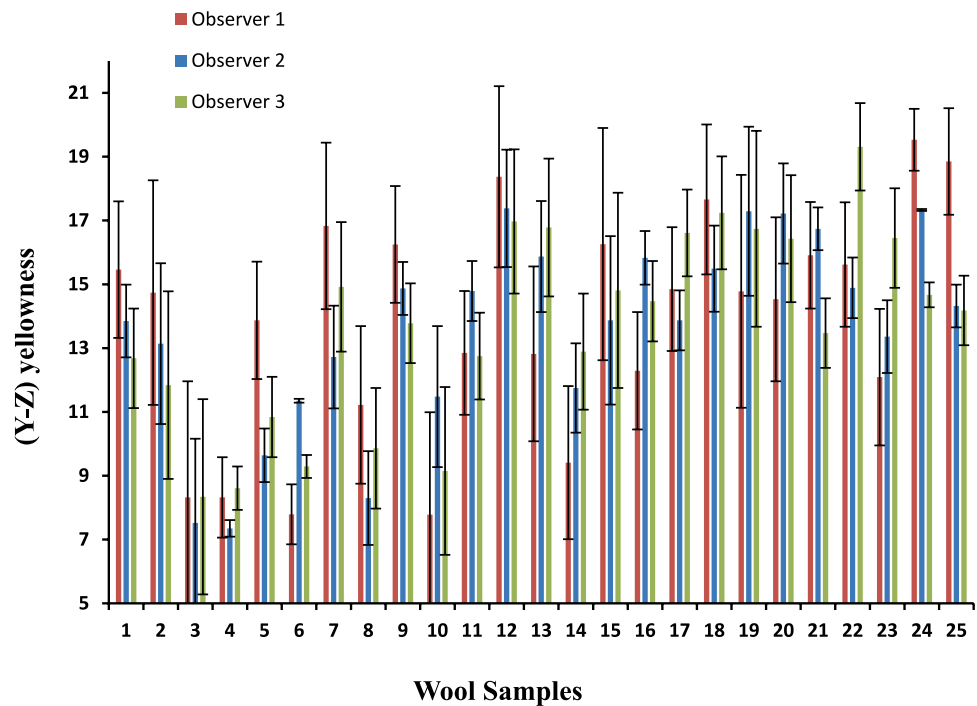
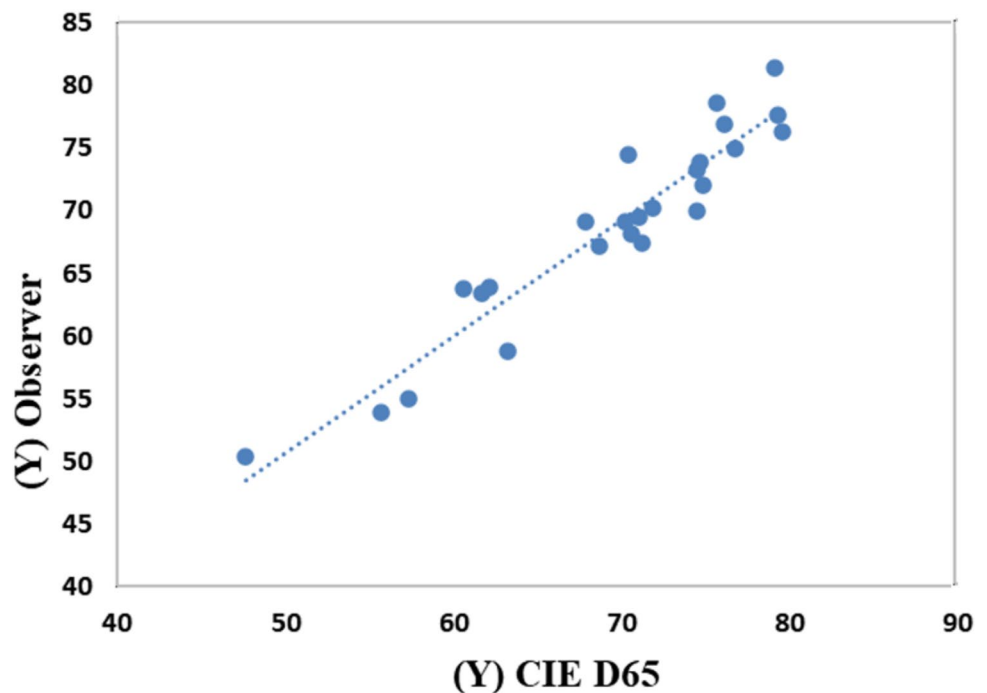


Fig. 8 Comparative analysis of brightness values between visual observation and spectral data



the case of some natural fibers, the ' a ' value in CIE Lab color space shows a very negligible value, and therefore, the final grade is assigned without the ' a ' value [32]. It is essential to represent color values by using three attributes in color science, but the conventional wool grading system does not fulfill this advanced criterion for better color assessment. This comprehensive approach is thought to be a

crucial necessity for precision in the grading process. Only two of these characteristics are usually regarded as conclusive for the final categorization in the actual application of natural fiber grading, which represents a major divergence. The observation that the third characteristic, namely the a^* value (Red/Green axis) in the CIE Lab color space, frequently provides negligible values for these fibers and hence

Fig. 9 Comparative analysis of yellowness values between visual observation and spectral data

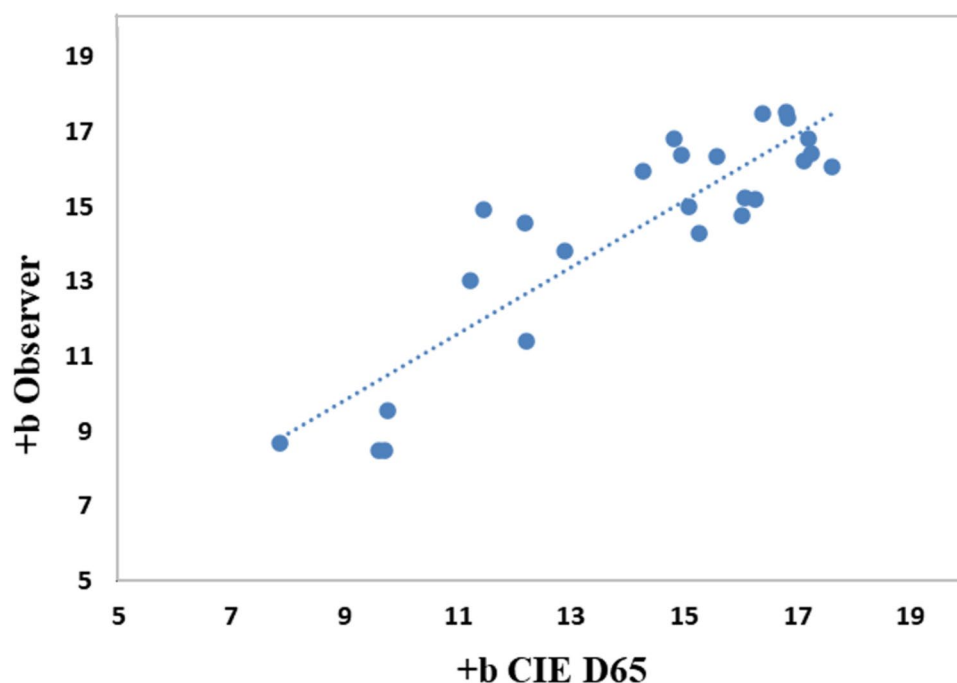


Table 4 Equation of the line for color attributes under D65 illuminant

Values	Illuminants	a (slope)	b (intercept)	R^2
Brightness	D65	0.92	4.26	0.9
Yellowness	D65	0.88	1.83	0.79

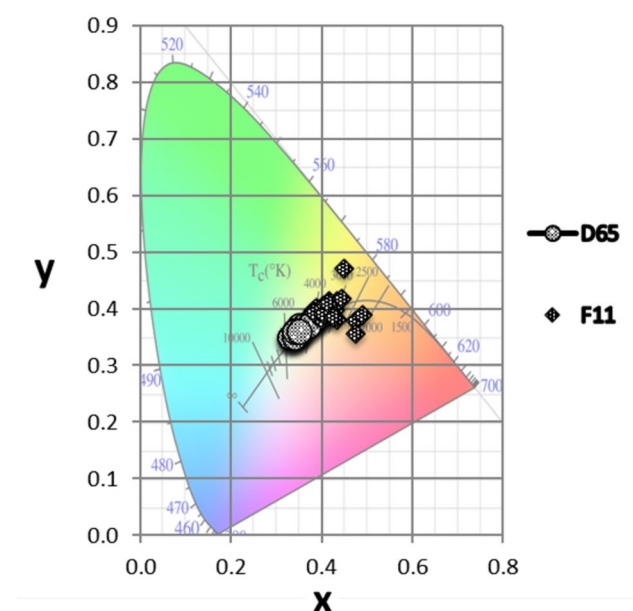


Fig. 10 Representation of wool color in CIE xyY color space

fails to contribute significantly to the grading choice justifies this simplification [33].

Similarly, arguments are often supported to describe the color of wool, and the two attributes are used for its color representation. Figure 13 shows that by changing the illuminant from D65 to F11, the color representation totally changes in the 3D color diagram. OriginPro software is used here to draw 3D color diagrams for the color representation of wool samples. Figures 14 and 15 show the color representation in CIE xyY color space in two different illuminants, and it can be seen clearly that three attributes play a vital role for accurate color measurement. This 3D model for color representation is a unique way and gives us a precise color measurement value. In this way, the disagreement between the visual and instrumental color measurement will also be negligible, and we will be able to get the same value of color as the observer sees in their final grading assigning process [34, 35]. This grading mechanism can be adoptive for all the natural fibers grading industry as it will positively decide their actual commercial cost. This will also enhance the possibility to characterize the color channels based on their brightness values. CIE xyY color space is considered to be the best possible choice for the representation of the wool color as it shows the chromaticity values.

Based on our findings, it is obvious that the proposed system is very easy to adopt at the commercial scale for the wool color grading because the proposed approach offers a comprehensive color evaluation system, precise color grading, and ability to convert color values into different color spaces. The current practices for the wool color grading are almost more than 50 years old, and there is a dire

Fig. 11 Wool color representation in 3D CIE Lab color space at D65 illuminant

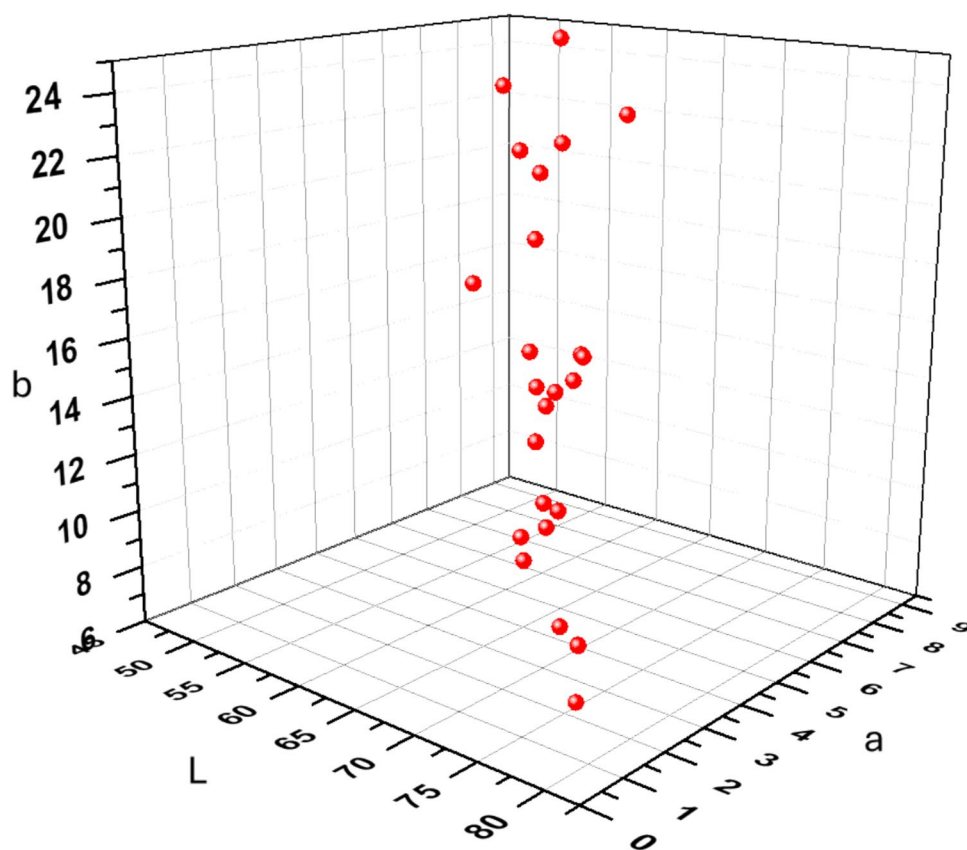


Fig. 12 Wool color representation in 3D CIE XYZ color space at D65 illuminant

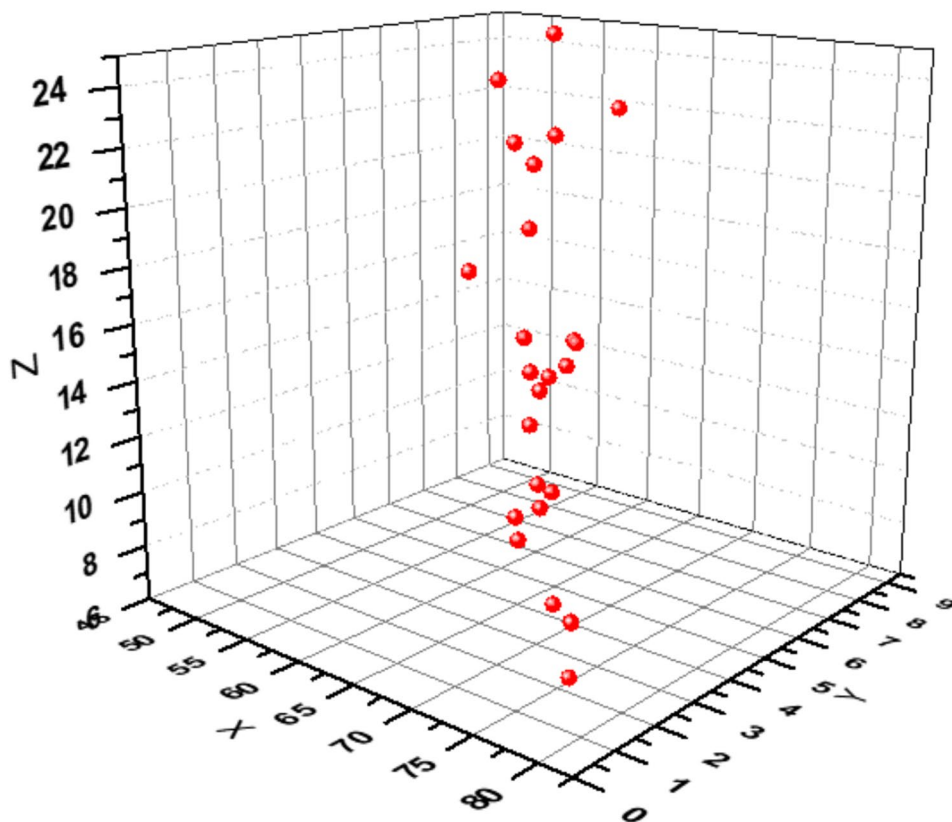


Fig. 13 Wool color representation at F11 illumination in 3D CIE XYZ color space

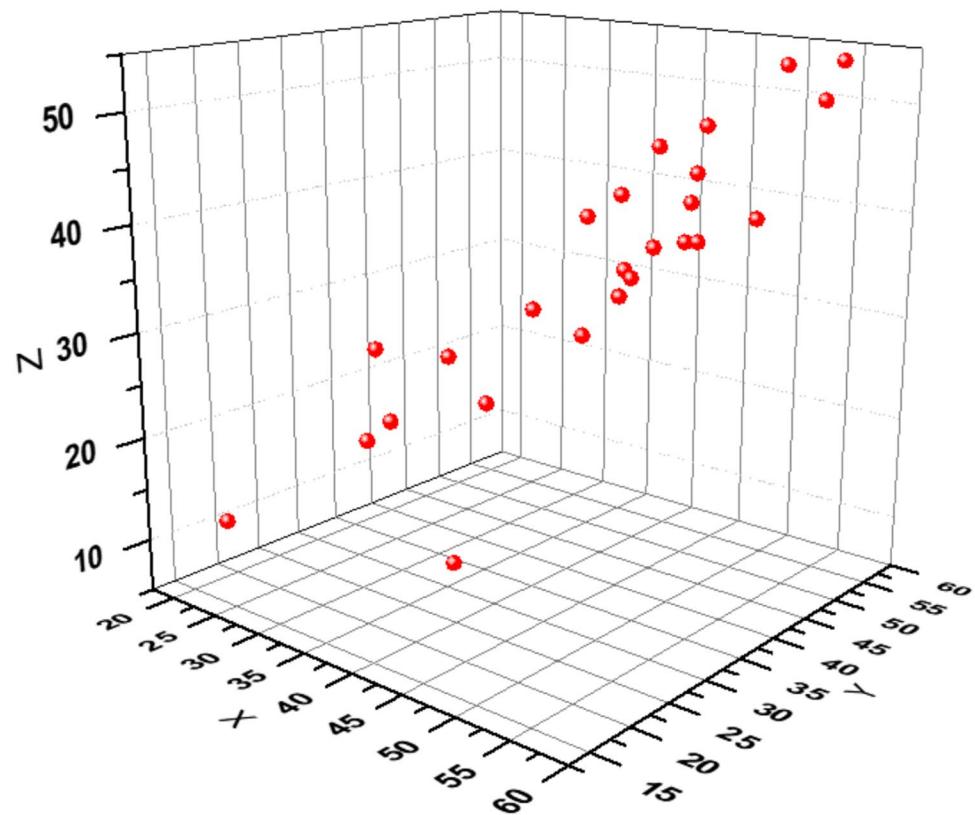


Fig. 14 Wool color representation at D65 illumination in 3D CIE xyY color space

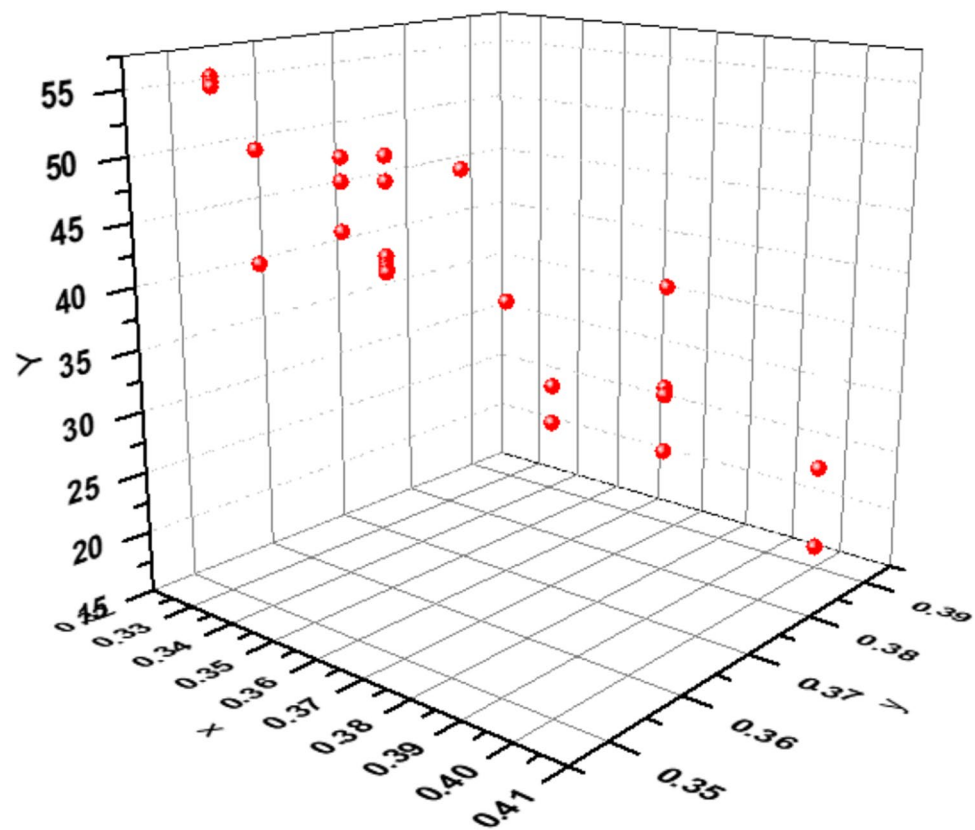
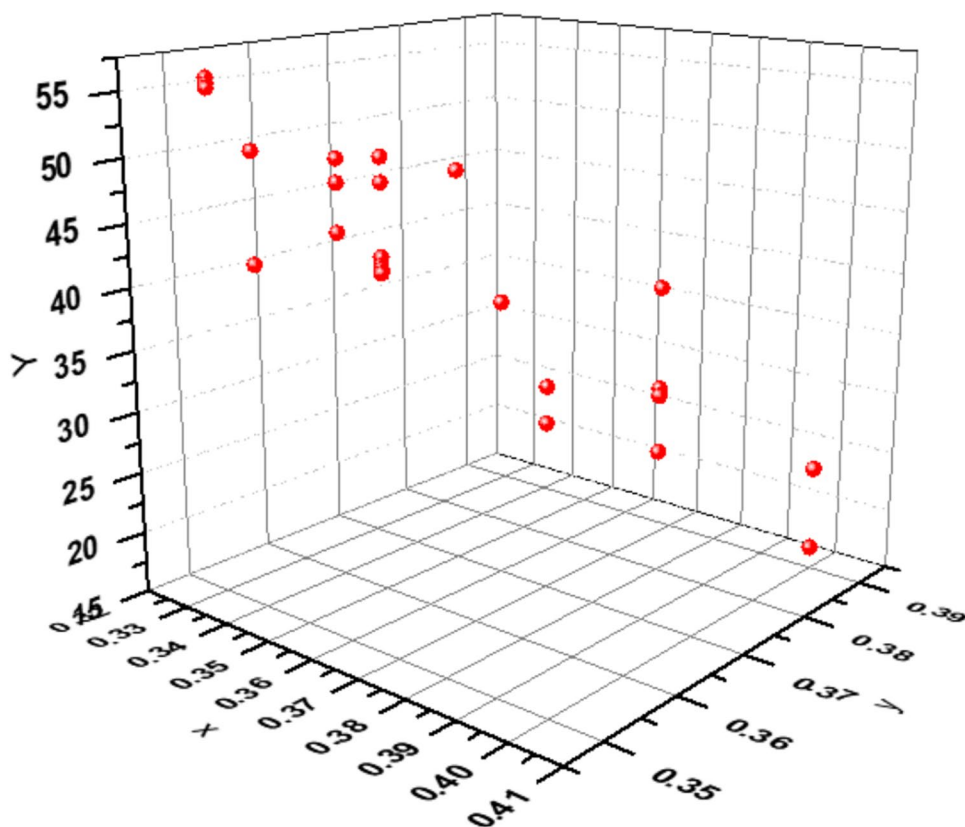


Fig. 15 Wool color representation at F11 illumination in 3D CIE xyY color space



need to introduce an upgraded and reliable system to meet the advanced and modern grading system used in different industries. The proposed color measurement technique can be a step toward the adoption of modern day color evaluation tool which are not only cost effective but also reliable for color evaluation.

The CIE xyY color space is not commonly used for the color grading of natural fibers. But the major advantage of using this color in the fiber grading is that the color can be represented in a 3D graph. It can also be seen that the color grade assigned to wool samples is very similar in both illuminants used in this research. The color represented in the CIE xyY color space is almost closer to the human vision system as the values are drawn from the CIE XYZ system, which uses spectral data for measurement [28, 35, 36].

In the context of the results, it is observed that the spectral data are the most important part for the color assessment of wool fiber and the human observer also relies on the spectral data for the color evaluation. The strong relationship between CIE values and visual assessment shows that this final grade should be assigned by the instrument using spectral data information. Different color spaces are also used in this research to describe the wool color in most precise manner. Even 3D color representation is used for the accurate color assessment to optimize the color standards according to the international standards in the current

era. Conventional attributes are very old and do not fully describe the wool color. This 3D multidimensional color representing model will be a huge contribution in the field of wool fiber color grading and reproducibility.

4 Conclusions

Several aspects that should be considered for the visual grading system of wool are examined within the parameters of this study project. The results show that the difference between the visual and instrumental color measurements can be minimized by using several color spaces and viewing angles throughout the visual grading process. It was discovered that the dark particles and oily wool samples were the main reason for the disparity. The wool is evaluated as bright by the classer, but the instrument gives it a different value since it thinks the color has faded. Due to its closer resemblance to the human visual system, this study has demonstrated that disagreement is extremely low simply by presenting color on spectral database space. Three characteristics can now be utilized for. Due to its closer resemblance to the human visual system, this study has demonstrated that disagreement is extremely low simply by presenting color on spectral database space. For accurate color assessment,

three characteristics can now be used, and new illuminants are recommended for the wool color depiction.

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Data Availability Data will be available on request.

Declarations

Conflict of Interest There are no conflicts of interests to declare.

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