# Wood Color Variation in Anatomical Sections of *Cedrus libani* from Two Mediterranean Regions

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Wood color is an important factor influencing the aesthetic and commercial value of timber products. This study aimed to clarify the natural color variation in Lebanon cedar (*Cedrus libani* A. Rich.) wood and its relation to anatomical structure and environmental conditions. Samples were collected from two regions in Türkiye (Kaş and Senirkent), differing in elevation and climate. Stem sections from four trees per region were analyzed by separating the pith, heartwood, and sapwood. Color properties were measured using a spectrophotometer in the CIE $L^*a^*b^*$ color space, resulting in 2670 data points. The results showed that sapwood exhibited the highest lightness values ($L^*$), with averages of 65.3 in Kaş and 65.8 in Senirkent, while pith displayed the lowest lightness (59.4 in Kaş, 61.6 in Senirkent). Total color differences ($\Delta E$) between anatomical parts frequently exceeded the perceptible threshold ($\Delta E > 3$), reaching up to 16.7 in the pith and 14.9 in the heartwood of some samples. Moreover, Kaş samples generally exhibited greater color variability than Senirkent, with average $\Delta E$ values of 13.4 (pith), 12.6 (heartwood), and 7.0 (sapwood), compared to 9.43, 10.57, and 6.14 in Senirkent, respectively. These findings highlight the combined influence of anatomical and environmental factors on wood color and provide insights for selecting timber for aesthetic purposes and enhancing visual quality in forest management.

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## INTRODUCTION

Wood's color is one of the most important factors determining the aesthetic appeal and market value of timber products. Beyond its structural applications, wood is widely used in interior design, furniture, and decorative elements, where natural color variations are essential for consumer preferences (Janin *et al.* 2001; Sedliačiková *et al.* 2021). Therefore, understanding the factors influencing wood color is crucial for both forest management and the wood industry. Among many tree species, Lebanon cedar (*Cedrus libani* A. Rich.) stands out as a valuable source of high-quality timber in Türkiye, making it a relevant species for investigating wood color variation. Today, Lebanon cedar is mostly found in the Taurus Mountains (Boydak 2003). Small populations, small groups, and individuals of the species can be found at elevations as low as 500 to 600 m and as high as 2400 m (Boydak 2003). Because of its superior wood, the Lebanon cedar is the most important and economically useful conifer species for Türkiye's Forest products industry (Bozkurt *et al*. 1990). Additionally, Lebanon cedar woods are essential for delivering significant environmental services and benefits, such as preserving biological diversity in the Taurus Mountains and safeguarding soil and water resources. Therefore, instruments that can consider the structures and unique features of cedar forests are necessary for the effective management planning of Türkiye's multipurpose forestry. To support forest management and timber resource planning methods, as well as to enhance knowledge about species development, data on the stand forest structure is essential in this context (Cao *et al.* 2010; Lima *et al*. 2017; Ciceu *et al*. 2021; Özçelik *et al*. 2023).

In these days, there has been an increasing focus on wood quality, and this has become one of the priority types of research of both forest growers (Laskowska *et al*. 2021; Thibaut and Gril 2021) and wood processors (FPL 2010). However, variations in the wood's natural properties (*e.g.*, color) in turn affects their end-use structural and aesthetic applications. To determine variations and properties that directly impact on end-use value of wood products, new advances in forest and wood science and other segregation technologies may help (Moore and Cown 2015). Therefore, knowledge on variation in wood properties is important when applying aesthetic purposes, particularly natural color is important. Moreover, it is also important in wood science to understand the implications of variations in end-product quality (Zobel *et al*. 1989; Miller 1999; Bowyer *et al*. 2003). Relating to this issue, the logging process may enable the benefits of improving wood aesthetic appearance to be better quantified by using instrumental analysis rather than visual appeal.

However, various methods have been developed for stochastic decision analysis (Jim and Liu 2001; Segura *et al*. 2014). The numerous growth index series have been published worldwide for different purposes (Pasanen 1998). It has been proposed that silvicultural information on trees is important to determine certain properties of wood (Jim and Liu 2001). It is well known that the different sections of wood have often demonstrated various physicochemical properties that the natural environmental conditions, notably climate, soil, and topography, could impact those variations (Jim and Liu 2001; Marini *et al*. 2021). However, a large range of natural wood patterns and colors can be obtained by special cutting (Miller 1999; Bowyer *et al*. 2003; FPL 2010). The appearance of wood in many end use applications, such as ornamental products, in households and in urban furniture, are some of the important issues at the moment. Therefore, it is very important to take into consideration external appearance that may be the most important criteria for the selection of wood.

Sahin and Onay (2020), ran a study that asked the question 'Is natural wood appearance impact on various types of uses important and relevant for wood-based applications?' The answer from the 600 people who responded to the questionnaire was a resounding 'yes'. It should be intuitively obvious that one of the main criteria in selectivity of wood depends on a good aesthetic appearance. However, the wood aesthetic characteristics can be evaluated by looking at the texture, figure, and color that naturally occurs (Bowyer *et al*. 2003). Some of the important issues for wood products to expect properties including natural appearance, color, durability, life cycle, and perceived quality (Sahin *et al*. 2020). In this sense, aesthetic lumber products could be an example that it must achieve certain strength requirements for a particular grade, but it also must meet the customers' expectations around color. When a significant proportion of the product falls outside acceptable limits, this creates a problem for the users as significant cost has already been incurred to make the product (Moore and Cown 2015). It is important to note that the color is a psyche sensation and an emotion that transmits a sensorial subjectivity of humans related to the different objects. Visual perception is generally under physiological control. Therefore, the quantitative colorimetry theory and technique consist in transforming sensorial impressions into numbers.

The wood parts, such as pith, heartwood, and sapwood, have been extensively researched across a wide range of tree species, with a large focus on commercial species. Numerous studies have focused on understanding the degree to which those parts and properties are affected by environmental, silvicultural, and genetic factors (Miller 1999; Young and Giese 2002; Šilinskas *et al*. 2020). Although the impacts of pith and heartwood on dimension lumber, engineered wood products, and pulp and paper are generally well known but there is limited research on impact of all those wood parts performance of newer products such as architectural practices. However, demonstrating the impact of wood property variation on end-product quality and expressing this in terms of a 'return to log' would enable the financial impact of improvements in wood quality to be calculated. In surface variations, either optical or botanical, that exist within logs, some defects, such as fiber orientations, annual ring anomalies, compression wood and internal checks, which often do not become apparent until the log has been sawn, can result in significant downgrading and loss of value (Bowyer *et al*. 2003; FPL 2010). It has been proposed that the timber (log) characteristics are closely related to juvenile wood pith (Bowyer *et al*. 2003; Pikk *et al*. 2004; FPL 2010). Therefore, silvicultural treatments that alter crown development of individual trees may have a direct effect on the quality of wood produced (Bowyer *et al*. 2003). For example, heartwood generally contains the innermost 10 to 12 annual rings from the pith; and such wood has lower stiffness, lower density, and a higher propensity to distortion due to higher longitudinal dimensional instability (Burdon *et al*. 2004). Therefore, heartwood is undesirable from a utilization perspective. Moore and Cown (2015) suggested that eliminating variability in the logs could reduce production costs approximately $22/m$^3$ wood product, mainly by reducing the difference between heartwood and sapwood. However, the heartwood impact on wood properties is well known and reducing these should be a major focus of forest management (Moore and Cown 2015).

In this study, to explore natural color variations and relationships with environmental factors, comprehensive studies have been conducted in Lebanon cedar wood (*Cedrus Libani* A. Rich), which was supplied from two geotropically different locations (forestlands). Therefore, the aim of this study was to evaluate color variation of wood prepared from different parts of Lebanon cedar trees. In this context, this study aimed to demonstrate the effect of variation in natural cedar wood color properties under different altitudes toward locations. To assess these variations, first, the sampling of cedar wood variations was standardized by taking cross-sections starting at 0.30 m from various trees of the selected cedar log; second, each representative disc was divided into three sections (pith, heartwood, and sapwood); third, the standard spectrophotometric method was used to find adequate measurements and comparisons. The research questions for this research are.

How to evaluate the color characteristics from log of the same wood species but different growing regions?

How to evaluate the colors of the different parts of the same wood species?

How to better understand, describe, and explain wood surface colors of different sections of surfaces of the same wood species.

## EXPERIMENTAL

### Materials

Lebanon cedar was used as the tree species in this study. In total, 2 regions were compared. A total of 4 trees were selected from each region. The selected regions were Antalya/Kaş and Isparta/Senirkent, which are in the Mediterranean and Mediterranean transition regions of Türkiye. The elevation of the study area in Kaş is between 1460 to 1575 m. In Senirkent, the elevation was 1644 to 1676 m. The pith, heartwood, and sapwood parts of the discs taken from different heights of the sample trees were analyzed. The study areas are shown in Fig. 1.

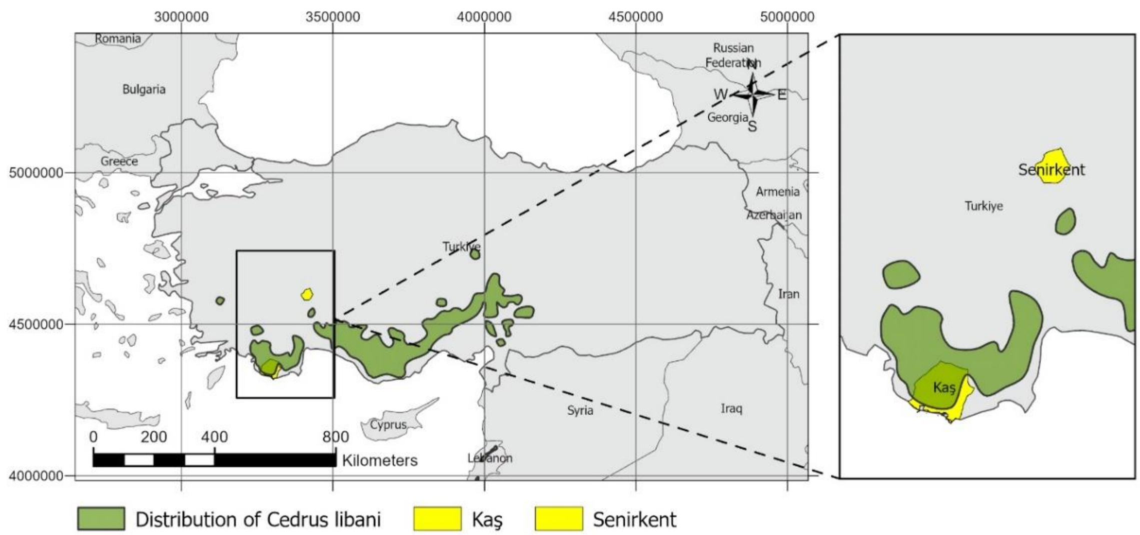


**Fig. 1.** Study areas

### Methods

Discs from cedar wood were obtained from the closest point to the ground. Sections were first taken at a height of 0.30 m above the ground.


**Fig. 2.** Disc images (a), sample disc processed in WinDENDRO program (b)

Then, as commonly used in forestry, they were taken at 2 m intervals such as 1.30, 3.30, 5.30, and 7.30 m according to the height of the tree. WinDENDRO program (Regent Instruments Inc., 2017) was used to determine the age and annual ring number of the selected trees. Figure 2 shows the disk samples obtained (a) and an image of a sample disk processed in the WinDENDRO program (b).

The $L^*$, $a^*$, $b^*$, and delta $E^*$ values were measured and compared in the pith, heartwood, and sapwood parts of the discs taken from the sample cedar trees at 2 m intervals starting from 0.30 m. The number of sections taken from the trees in Kaş region was determined as 9 (1$^{st}$ tree), 11 (2$^{nd}$ tree), 12 (3$^{rd}$ tree), and 12 (4$^{th}$ tree) for 4 trees, respectively. The cross-section numbers of the trees in Senirkent region were determined as 10 (1$^{st}$ tree), 10 (2$^{nd}$ tree), 11 (3$^{rd}$ tree), and 12 (4$^{th}$ tree). Calculations were made by averaging the color values of the trees. For ease of data presentation, Kaş and Senirkent regions were coded as A and B, respectively, anatomical sections as X (pith), Y (heartwood) and Z (sapwood), and trees as I, II, III and IV. Mean color values were calculated for each anatomical section and tree and comparisons were made between sections, trees and regions to examine variation in wood color.

## Color Measurements

Color measurements of the wood samples were performed using an X-Rite 962 spectrophotometer (Grand Rapids, MI, USA) with a D65 standard light source at 6500 K and a 2° standard observer angle. The total color differences ($\Delta E^*$) for each of the resulting discs were performed through Eq. 1 below.

$$\Delta \boldsymbol{E}^* = \sqrt{(\Delta \boldsymbol{L}^*)^2 + (\Delta \boldsymbol{a}^*)^2 + (\Delta \boldsymbol{b}^*)^2} \tag{1}$$

where $L^*$ represents the degree of brightness/darkness (having a value between 0 and 100, where a lower number indicates greater darkness; 0 denotes black, while 100 represents perfect whiteness), $a^*$ indicates the degree of redness ($a^*$+) or greenness ($a^*$-) and $b^*$ denotes the degree of yellowness ($b^*$+) or blueness ($b^*$-). $\Delta E^*$ describes the total color difference as a combination of these factors. Prior to measurement, the surface of each wood disc was sanded with fine-grit sandpaper to create a smooth and uniform surface and allowed to stabilize under laboratory conditions (20 ± 2 °C temperature and 65 ± 5% relative humidity) to minimize environmental effects on color. To minimize measurement errors and ensure repeatability, the spectrophotometer was calibrated before each measurement session using a standard white calibration plate according to the manufacturer's instructions. All measurements were performed by the same person to reduce human variability. Measurements were taken on the pith, heartwood, and sapwood sections of each disc. For each anatomical part, 10 replicates were conducted at randomly selected points, and the mean values were calculated. Graphs were prepared by averaging these data. A total of 2670 measurements were taken for each disc of the cedar tree in total for 8 trees, separately for the pith, heartwood, and sapwood sections.

# RESULTS AND DISCUSSION

Table 1 shows the general growing conditions of tree samples selected in this study. The average differences of selected trees for age were measured to be approximately 9 years (96 ± 16 for Group A, 95 ± 20 for Group B). Average tree length differences were found to be approximately 1.82 m (21.5 ± 2.6 m for Group A, 19.68 ± 1.5 m for Group B), and for growing altitude differences was found to be approximately 126 m (1533 for Group A, 1659 for Group B), respectively. Although many of the important wood properties that affect end-product performance are under strong genetic control, Table 1 might suggest that different growing conditions could impact on many key wood properties, including visual features (Young and Giese 2002).

**Table 1.** Tree Samples' General Growing Conditions (A: Kaş, B: Senirkent)

| Trees | Average Age of Trees (years) | Average Length of Trees (m) | Altitude (m) |
|---|---|---|---|
| A | | | |
| I | 112 | 24.1 | 1460 |
| II | 92 | 19.8 | 1550 |
| III | 85 | 20.2 | 1575 |
| IV | 94 | 22.0 | 1549 |
| Ave. | 96 | 21.50 | 1533 |
| B | | | |
| I | 95 | 21.35 | 1662 |
| II | 107 | 18.0 | 1644 |
| III | 113 | 20.7 | 1676 |
| IV | 103 | 18.7 | 1655 |
| Ave. | 105 | 19.68 | 1659 |

The type and number of chemical constituents could be influenced by the natural color of woods, even in the same species. It has already been well predicted that wood color could vary in different parts, from bark to pith, and root to crown (Miller 1999; FPL 2010). In this respect, a total of eight Lebanon cedar woods from two different regions (four from each region) of the Mediterranean part (Kaş and Senirkent forestlands) of Türkiye were evaluated. Figures 1 and 2 show comparative three-color coordinate ($L*a*b*$) properties of wood samples from two different regions (Kaş (A) and Senirkent (B)) obtained from three different sections (pith, heartwood, and sapwood) of the same discs at different section heights (between 1 to 12 discs). It appears complex to evaluate all this data. Therefore, some general evaluations have been made for each coordinate property rather than explaining all values. However, all measured samples revealed significant variability. This could be expected, considering there have been numerous literature reports on these growth variations for different kinds of wood species (Zobel *et al*. 1989; Young and Giese 2002; Pikk *et al*. 2004; Šilinskas *et al*. 2020; Marini *et al*. 2021; Thibaut and Gril 2021).

During the evaluation of wood properties, the terms of 'sapwood', 'heartwood', and 'pith' are confusing. Some researchers have used the terms synonymously, while others have used each term in a more restricted sense to imply the region of a timber where wood structure and properties are influenced by ring number from the pith, or by crown size. Because of distinct different anatomical and chemical properties, wood discs were separated into three parts that are the center of tree as pith, dark part of cross section of discs as heartwood, and between heartwood to bark as sapwood. The color characteristics of each of these sections are summarized under the following headings.

## Individual Color Coordinate Properties Evaluations for Samples

It is well established that pith is the central wood of the tree and composed of soft, porous structure containing spongy parenchyma cells, which in some cases can store starch. It is vital to the storage and transportation of nutrients when the tree was young. Its color is usually like heartwood and considered to be an important appearance during log processing of lumber. For the color properties of piths, the lightness ($L^*$) values were found to be in the range of $L^*AX_{II4}$: 49.9 to $L^*AX_{IV1}$: 71.6 for group A- and ranged from $L^*BX_{IV4}$: 51.8 to $L^*BX_{II2}$: 71.1 for group B woods. However, the redness-greenness ($a^*$) values were found to be in the range of $a^*AX_{III10}$: 1.84 to $a^*AXI_{V1}$: 13.1 for group A- and ranged from $a^*BX_{IV1}$: 4.27 to $a^*BX_{III4}$: 17.4 for group B woods. Moreover, the yellowness-blueness ($b^*$) properties were found to be in the range of $b^*AX_{IV1}$: 26.4 to $b^*AX_{IV4}$: 43.4 for group A and ranged from $b^*BX_{II4}$: 26.0 to $b^*BX_{II7}$: 42.8 for group B woods. The colorimetric value revealed a considerable variation for all color coordinate values. The highest and lowest value difference within same group of trees were also calculated and found to be $\Delta L^*XA_{max-min}$: 21.7 and $\Delta L^*XB_{max-min}$: 19.2 for lightness ($L^*$), $\Delta aXA_{max-min}$: 11.3 and $\Delta a^*XB_{max-min}$: 13.2 for redness ($a^*$), and $\Delta b^*XA_{max-min}$: 16.9 and $\Delta b^*XB_{max-min}$: 16.8 for yellowness ($b^*$). Those values represent the color coordinates differences between two group of woods is $\Delta L^*$XA-B: 2.4, $\Delta a^*$XA-B: -1.9, $\Delta b^*$XA-B: 0.2, respectively.

However, the pith is enclosed by the wood, which can be divided into the heartwood and the sapwood, which is closest to the bark. The term pith was used for indicating the central region of the log where structure and properties are variable and differ from those of the sapwood. For the color properties of heartwood, the lightness ($L^*$) values were found to be in the range of $L^*AY_{III1}$: 50.1 to $L^*AY_{I1}$: 71.2 for group A- and ranged from $L^*BY_{IV10}$: 54.5 to $L^*BY_{IV2}$: 72.0 for group B woods. The $a^*$ color coordinate values were found to be in the range of $a^*AY_{II2}$: 4.5 to $a^*AY_{I12}$: 12.2 for group A- and range from $a^*BY_{IV1}$: 3.3 to $a^*BY_{IV3}$: 14.2 for group B woods. However, the $b^*$ color coordinate values were found to be in the range of $b^*AY_{IV1}$: 26.1 to $b^*AY_{VI6}$: 43.4 for group A-, and it ranged from $b^*BY_{II4}$: 27.6 to $b^*BX_{III5}$: 40.9 for group B woods. When comparing two group of woods at similar treatment conditions, all color coordinate values showed some variations. The highest and lowest value difference within same group of trees were found to be $\Delta L^*AY_{max-min}$: 20.1 and $\Delta L^*B_{max-min}$: 17.5 for lightness ($L^*$), $\Delta a^*YA_{max-min}$: 7.6 and $\Delta a^*YB_{max-min}$: 10.9 for redness ($a^*$), and $\Delta b^*YA_{max-min}$: 17.3 and $\Delta b^*YB_{max-min}$: 13.3 for yellowness ($b^*$). Those values represent the color coordinates differences between two group of woods is $\Delta L^*$YA-B: 2.6, $\Delta a^*$YA-B: -3.21, $\Delta b^*$YA-B: 4.0, respectively.

The cells in heartwood are dead and some were clogged up with extractives that they cannot carry nutrients and water, which have a relatively low moisture content (30 to 50%). In contrast to pith and heartwood, the sapwood's cells are alive and contain the nutrient-carrying parenchyma cells. Those provide the tree with a delicate physicochemical arrangement. For the color properties of sapwood, in terms of lightness properties, it was found to be in the range of $L^*AZ_{I12}$: 59.73 to $L^*AZ_{I1}$: 71.94 for group A- and ranged from $L^*BZ_{I6}$: 60.1 to $L^*BZ_{II2}$: 72.3 for group B woods. In terms of redness properties, they were found to be in the range of $a^*AZ_{I5}$: 4.5 to $a^*AZ_{I12}$: 10.1 for group A- and ranged from $a^*BZ_{III1}$: 1.7 to $a^*BZ_{II1}$: 12.6 for group B woods. In terms of yellowness properties, they were found to be in the range of $b^*AZ_{III1}$: 25.9 to $b^*AZ_{II6}$: 35.1 for group A- and ranged from $b^*BZ_{III1}$: 28.1 to $b^*BZ_{III7}$: 36.1 for group B woods. When comparing two group of woods at similar treatment conditions, all color coordinate values show some variations, the highest and lowest value difference within same group of trees were found to be $\Delta L^*AZ_{max-min}$: 12.2 and $\Delta L^*ZB_{max-min}$: 12.2 for lightness ($L^*$), $\Delta a^*ZA_{max-min}$: 5.5 and

$\Delta a^*ZB_{max-min}$: 10.8 for redness ($a^*$), and $\Delta b^*ZA_{max-min}$: 9.2 and $\Delta b^*ZB_{max-min}$: 8.0 for yellowness ($b^*$). Those values represent that the color coordinates differences between two group of woods were $\Delta L^*$ZA-B: -0.01, $\Delta a^*$ZA-B: -5.3, $\Delta b^*$ZA-B: 1.2, respectively.


**The disc number represents the cross-sections taken from the stem, starting from the base of the tree (Disc 1, closest to the ground) and increasing upwards toward the top of the tree.**

**Fig. 3.** Color coordinate properties of woods supplied from Kaş region (A)

In summary, when Figs. 3 and 4 were carefully reviewed within measured findings, wood samples obtained from different heights (discs) appeared to exhibit some level color variations not only in the same logs but also among logs and supplied geographical regions. No clear trend was found between sampling heights and geographical regions. However, this data clearly reveals the phenomenon for determining the exact colors of wood that are influenced by many parameters. There have been many literature reports indicating that it is important to understand the implications of forest practices on wood end-product performance, particularly color and related properties (Zobel *et al*. 1989; Miller 1999; Pikk *et al*. 2004; Šilinskas *et al*. 2020; Marini *et al*. 2021; Thibaut and Gril 2021). Regarding this issue, if the goal is to grow quality clear wood for aesthetic appearances, what sites should be selected and what tree stocks and management regimes should be employed? (Moore *et al*. 2012). It is therefore important to understand the effects of changes in wood properties on final product quality.

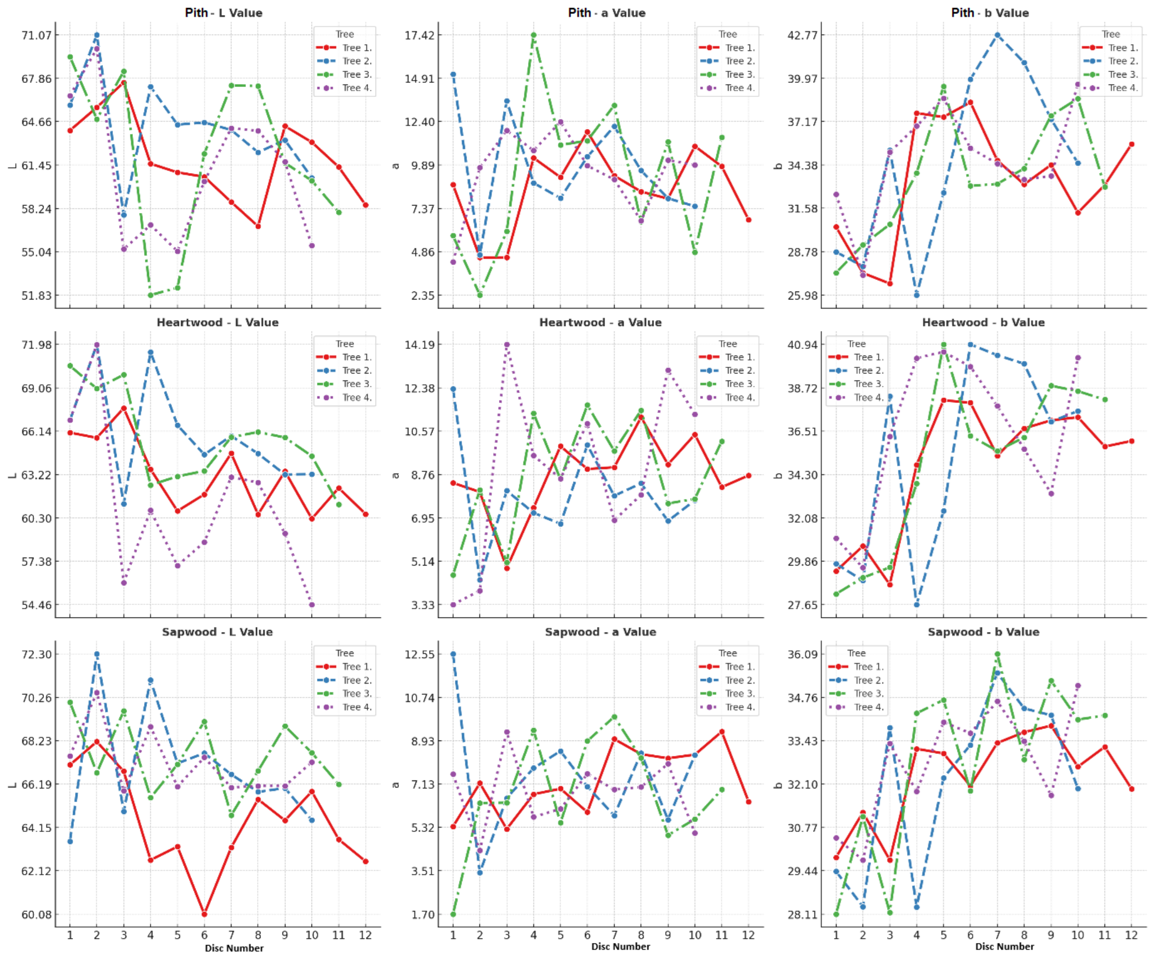


**Fig. 4.** Color coordinate properties of woods supplied from Senirkent region (B)

## The Average Color Coordinate Properties Evaluations for Samples

It has already been well-established that some of the factors that affect end-product wood quality are closely related to the growing condition of trees. However, variation in these characteristics within a log, for example, from pith to bark or root to crown, results in a variety of wood properties, particularly natural appearance (Moore and Cown 2015). Regarding former literature findings, it was hypothesized that Lebanon cedar woods supplied from two different regions could influence color properties in a measurable range. The data presented in Figs. 3 and 4 are heavy and difficult to evaluate easily. Therefore, average values for each part and group of woods were calculated to summarize the data presented in Figs. 3 and 4 and make clear comparisons. The average color properties of different sections of wood that were supplied from two different geographical regions are presented in Table 2. For color values of piths, the woods from Senirkent region (B) appear to show marginally higher lightness ($L^*$) (LAX: 61.6, LBX: 62.3) and redness ($a^*$) ($a^*$AX: 8.5, LBX: 9.2) while lower yellowness ($b^*$) ($b^*$AX: 6.6, $b^*$BX: 5.9) color coordinate values, compared to counterpart samples. For heartwoods, the woods from Senirkent (B) show marginally higher $L^*$ (LAY: 62.6, LBY: 63.9) and $a^*$ ($a^*$AY: 8.30, $a^*$BY: 8.59), but lower $b^*$ ($b^*$AY: 35.8, $a^*$BY: 35.3), values compared to counterpart samples. It is worth mentioning that, like pith and heartwoods, almost similar results were also found for sapwood samples that all color coordinates revealed only marginal differences between the two groups *L** (*L**AZ: 66.6, *L**BZ: 66.4) and *a** (*a**AZ: 7.1, *a**BZ: 7.0), and *b** (*b**AZ: 32.1, *a**BZ: 32.5).

**Table 2.** Average Color Coordinate Properties of Samples

| Color Coordinates | Kaş (A) | Senirkent (B) |
|---|---|---|
| | Pith | |
| *L** | 61.6 | 62.3 |
| *a** | 8.5 | 9.2 |
| *b** | 35.4 | 34.0 |
| | Heartwood | |
| *L** | 62.6 | 63.9 |
| *a** | 8.3 | 8.6 |
| *b** | 35.8 | 35.3 |
| | Sapwood | |
| *L** | 66.6 | 66.4 |
| *a** | 7.1 | 7.0 |
| *b** | 32.2 | 32.5 |

To evaluate the average total color difference (Δ*E**) of similar parts but from different regions of the same tree species, the calculated total color difference values are given in Fig. 5. It is clearly apparent that group A wood samples showed higher color difference properties for all three parts compared to group B of trees. For piths, it was found to be high for both groups and could be a visually perceived range (Δ*E**AX: 6.6 and Δ*E**BX: 5.9), but differences between the two groups were found to be only for Δ*E**AX-BX: 0.7.

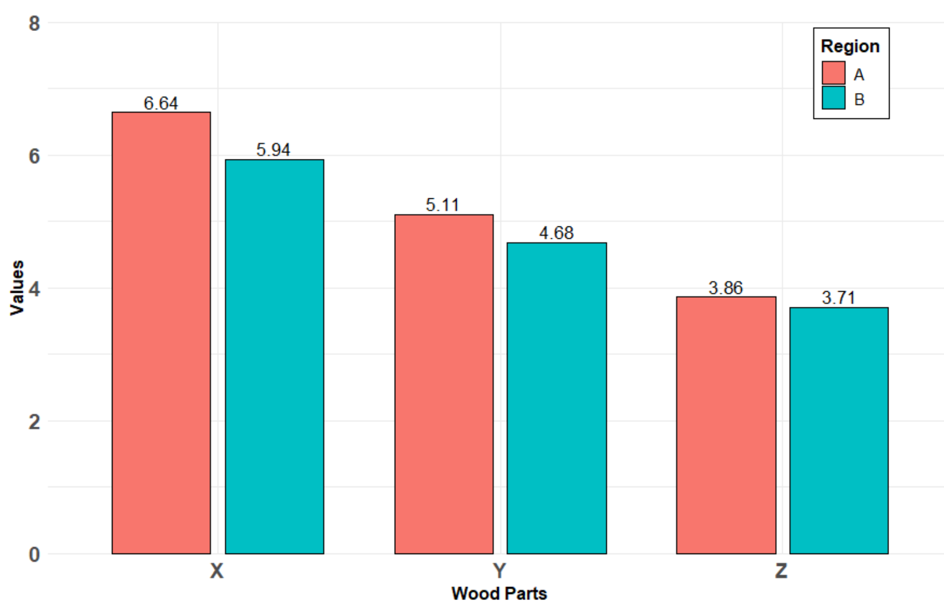


**Fig. 5.** The average total color difference (ΔE) of wood samples (X: Pith, Y: Heartwood, Z: Sapwood)

Similar results were also observed for heartwoods that heartwoods from the two groups showed easily perceived color difference properties ($\Delta E^*$AY: 5.1 and $\Delta E^*$BY: 4.7) but differences between the two groups were found to be only $\Delta E^*$AY-BY: 0.5. For sapwood, fewer color differences were found than pith and heartwoods that it was found to be $\Delta E^*$AZ: 3.9 for A groups and $\Delta E^*$BZ: 3.7 for B groups of trees that were considered high enough to be perceived visually, but only sapwoods ($\Delta E^*$AZ-BZ: 0.2) showed marginally different values between two group of samples.

## The Controls Color Coordinate Properties Evaluations for Samples

There are many literature reports on tree and wood properties as affected by forest practices. It is thought that samples taken from the breast height of trees may be useful for assessing wood properties. In this sense, the data presented in Figs. 3 and 4 were summarized and clearer comparisons made; the wood samples taken from the breast height of trunks (1.30 m) are considered as control discs (disc number 2). The color coordinate properties (CIE $L^*a^*b^*$) of three different wood parts from two different geographical regions are presented in Table 3.

It is clearly apparent that all three wood parts showed some variations that were not only for the same groups of trees, but also between two different groups (A and B). Those could be expected, considering the growth conditions besides geographical situations. Within the group of trees, considerable differences were found among parts of the tree that sapwood appeared to show the highest lightness ($L^*$AZ: 65.3, $L^*$BZ: 65.8) followed by heartwood ($L^*$AY: 60.9, $L^*$BY: 62.3) and pith ($L^*$AX: 59.4, $L^*$BX: 61.6). The lightness properties, which are independent of hue or color, reveal a clear trend like sapwood > heartwood > pith for both groups of trees. However, the color coordinate properties of redness–greenness ($a^*$) and yellowness-blueness ($b^*$) show different trends than lightness within parts and between groups. The highest redness values were found with heartwood ($a^*$AY: 9.0, $a^*$BY: 9.0) for both group samples, but some variations were found for other parts of trees. The redness values were found to be heartwood ($a^*$AY: 9.0) > sapwood ($a^*$AZ: 8.0) > pith ($a^*$AX: 6.3) for group A, and heartwood ($a^*$BY: 9.0)> pith ($a^*$BX: 8.2) > sapwood ($a^*$BZ: 7.2) for group B samples, in that order. The more complex results were also found for $b^*$ color coordinate than the highest yellowness values of ($b^*$AX: 35.9) followed by ($b^*$AY: 35.1) and ($b^*$AZ: 31.6) were found for A groups, while the highest yellowness values of ($b^*$BY: 36.4) followed by ($b^*$BX: 35.7) and ($b^*$BZ: 33.3) were found for B groups.

Because of woods optical complexity, even the same tree parts, it seems quite difficult to predict the exact color variations of Lebanon cedar wood from different geographical conditions. However, the measurement of the appearance of the woods can allow us to understand the utility of the determination performed with the CIE$L^*a^*b^*$ system to compare the pith, heartwood, and sapwood along the same parts (discs) or to compare the same sections along the heights of the same tree.

In many cases, color differences (hue) can be easily realizable, but numerical values are important in scientific evaluations. However, color variations within similar samples are usually the quantity of total color change ($\Delta E^*$) that is calculated based on the color coordinate values. To evaluate color variation for control samples for each part, the total color change values ($\Delta E^*$) were calculated from color coordinate values ($L^*a^*b^*$) and plotted in Fig. 6 (Fig. 6X for pith, Fig. 6Y for heartwood, and Fig. 6Z for sapwood).

**Table 3.** The Color Coordinate (CIE *L*a*b**) Properties of Wood Samples

| Trees | Pith (X) | | | Heartwood (Y) | | | Sapwood (Z) | | |
|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | |
| | *L** | *a** | *b** | *L** | *a** | *b** | *L** | *a** | *b** |
| I | 58.95 | 6.0 | 35.74 | 60.16 | 8.67 | 36.25 | 60.92 | 7.54 | 34.35 |
| II | 58.62 | 1.84 | 37.07 | 59.81 | 7.97 | 33.91 | 65.97 | 9.84 | 31.57 |
| III | 63.44 | 10.61 | 36.75 | 63.71 | 9.47 | 35.09 | 67.93 | 6.65 | 31.16 |
| IV | 56.71 | 6.86 | 33.87 | 59.76 | 9.93 | 35.19 | 66.24 | 7.92 | 29.46 |
| Ave. | 59.43 | 6.33 | 35.86 | 60.86 | 9.01 | 35.11 | 65.26 | 7.98 | 31.64 |
| B | | | | | | | | | |
| I | 61.30 | 9.80 | 33.08 | 62.31 | 8.23 | 35.72 | 63.59 | 9.31 | 33.24 |
| II | 63.29 | 7.95 | 37.33 | 63.22 | 6.82 | 36.99 | 66.00 | 5.64 | 34.21 |
| III | 60.29 | 4.82 | 38.66 | 64.46 | 7.74 | 38.55 | 67.66 | 5.66 | 34.08 |
| IV | 61.68 | 10.17 | 33.66 | 59.24 | 13.12 | 33.33 | 66.10 | 7.97 | 31.75 |
| Ave. | 61.64 | 8.19 | 35.68 | 62.30 | 8.97 | 36.14 | 65.84 | 7.15 | 33.32 |

It appears there was not any clear trend between the sampling regions (A and B) and parts of wood (X-, Y- and Z parts), and complex results were found with color. However, the highest level of total color changes values of Δ*E**AX: 16.7 and Δ*E**AY: 14.9 were found with pith and heartwood samples from IV. tree and Δ*E**AZ:12.0 in sapwood from I. tree, respectively. It is also noticeable that the average total color difference values appear to be higher for A group of wood samples compared to B group of wood samples for all three sections that were measured as Δ*E**AXAveg: 13.4, Δ*E**BXAveg: 9.4 for pith, Δ*E**AYAveg: 12.6, Δ*E**BYAveg: 10.6 for heartwood and Δ*E**AZAveg: 7.0, Δ*E**BZAveg: 6.1 for sapwood, respectively.

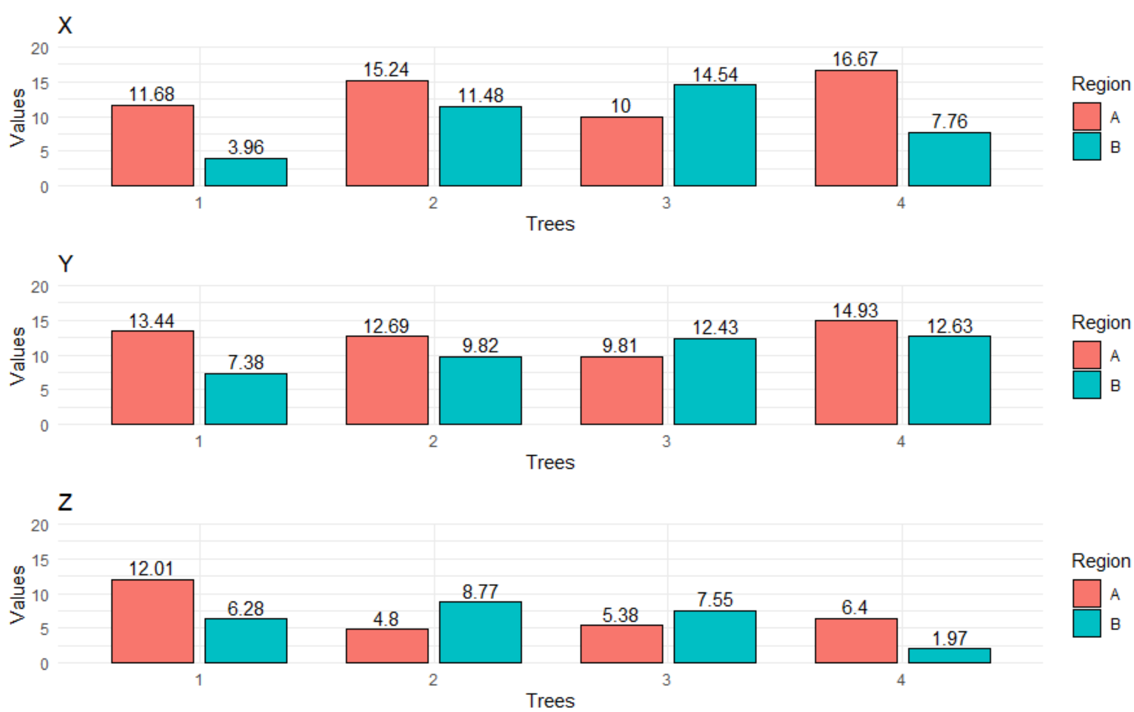


**Fig. 6.** Color difference (Δ*E** properties of trees (X: Pith, Y: Heartwood, Z: Sapwood)

Those results could be a good prediction on the appearance variation in wood properties that could occur not only in the same stands but also in different geographical places. However, there still needs to be clear results when comparing growing conditions' impact on the optical properties of wood. It has been hypothesized that if Δ*E** is <1.0, it is not perceptible by the human eye, 1.0 < Δ*E** < 1 to 3, it is perceptible through close observation, and >3, it is perceptible immediately

Δ*E** properties presented in Fig. 6 reveal a clear conclusion that the color difference between wood sections, even the same tree could be perceived by human eye.

It has been clearly proposed that some of the key wood properties that affect timber physical properties within and between trees are required to predict lumber performance (Moore and Cown 2015). In this sense, spectrophotometric color evaluations could be useful from the internal wood properties distribution within a log and/or external wood properties distribution from different regions of the same species. In this study, it was clearly demonstrated that the variation in wood color properties occurs not only in Lebanon cedar growing locations but also withing the same logs.

## CONCLUSIONS

1. This study revealed that natural color variation in Lebanon cedar wood varied significantly both between anatomical sections (pith, heartwood, sapwood) and between different geographical regions. However, in general, differences between anatomical sections were more pronounced than regional differences. *L**, *a**, *b** and Δ*E** values obtained from spectrophotometric measurements showed that the highest lightness (*L**) values were observed in sapwood, followed by heartwood and pith in both regions. For example, the average lightness values were 65.3, 60.9, and 59.4 for sapwood, heartwood and pith, respectively, in the Kaş region; and 65.8, 62.3, and 61.6, respectively, in the Senirkent region.
2. Redness (*a**) and yellowness (*b**) values showed a more complex distribution. In general, heartwood had the highest redness values, while differences were observed between sapwood and heartwood regions. Yellowness values were generally higher in the heartwood and sapwood regions, which varied between samples. These results indicate that variations in wood color cannot be explained by a single factor and that the interaction of anatomical structure and growing environment is effective on these differences.
3. The total color difference (Δ*E**) between anatomical sections was above the visual perception threshold (Δ*E** > 3) in most cases, indicating that these differences were visually significant. The highest color difference was observed in the pith region (Δ*E**AX: 16.7) and heartwood region (Δ*E**AY: 14.9) in some trees. In terms of mean Δ*E** values, samples from the Kas region were higher than those from the Senirkent region, suggesting that regional environmental conditions contribute to color variation.
4. Δ*E* values are in many cases above visually perceptible limits, indicating that these variations are not only quantitative but also meaningful in terms of user experience. Therefore, regional growth conditions and anatomical characteristics of wood should be considered for both forest management and industrial product standardization.
5. In summary, the findings concretely demonstrated not only the industrial and aesthetic value of wood color, but also that it varied depending on regional and

structural differences. These results provide a scientific basis for future studies on wood quality variation and offer practical insights for the forest products industry to optimize raw material selection and improve visual quality standards in wood-based products.

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