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Detection of Biochemical Variations in Natural and Artificially Ripened Fruits Using Spectral Analysis

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Abstract*— As artificial fruit ripening can change a fruit's natural biochemical makeup, it is frequently challenging to tell the difference between naturally ripened and artificially ripened fruits by visual inspection. This study uses spectral reflectance analysis to examine biochemical differences between naturally ripened bananas, mangos, and apples and those that are artificially ripened. An ASD FieldSpec 4 spectroradiometer was used to collect spectral data between 350 and 2500 nm in wavelength. 180 banana, 330 mango, and 200 apple spectra made up the extensive library of 1,430 spectral characteristics. Preprocessing, such as noise reduction, second-derivative transformation, and normalisation, was applied to the gathered spectral data. For both the naturally ripened and artificially ripened groups, mean reflectance was computed separately at each wavelength to generate typical spectral patterns. The visible, near infrared, and short-wave infrared regions all showed distinct differences when the mean spectral fingerprints were compared. Significant variations were found in the following regions: 400–699 nm for pigments, 700–999 nm for internal tissue structure, roughly 970 nm for water, 1000–1300 nm for sugars and carbohydrates, roughly 1450 nm for moisture, roughly 1900 nm for the water combination band, and 2100–2300 nm for organic compounds. Around 970, 1450, 1900, and 2200 nm were the most noticeable and prevalent differences among the three fruits. Variations in water distribution, moisture, sugars, starch, carbohydrates, pigments, and other organic components related to the ripening process are indicated by these spectrum variances. The results show that broad-range spectrum analysis can offer a quick and non-destructive method for identifying biochemical differences and distinguishing between naturally ripened and artificially ripened fruits.

Keywords: ASD FieldSpec 4, spectral signature, detection, banana, mango, apple, wavelength analysis.

I. INTRODUCTION

Because they include carbs, vitamins, minerals, dietary fibre, antioxidants, and other bioactive substances, fruits are a vital part of the human diet. The ripening process, which involves a number of physiological and biochemical changes, has a significant impact on fruit quality. alterations in carotenoid and chlorophyll pigments, the transformation of starch into soluble sugars, the alteration of organic acids, the softening of tissues, and variations in moisture and water content are some examples of these alterations. Because light absorption and reflectance are directly impacted by the fruit's biochemical makeup and physical structure, the optical and spectral characteristics of fruit also alter as it ripens.

The intricate physiological process of natural fruit ripening is mostly controlled by endogenous plant hormones, especially ethylene in climacteric fruits. Respiration, pigment composition, sugar content, acidity, stiffness, and moisture all gradually change during this process. However, the adoption of artificial ripening techniques has been promoted by the commercial desire for quickly accessible and consistently ripened products. The ripening process can be accelerated by a number of external substances, and calcium carbide has been extensively documented as a dangerous artificial ripening agent. Acetylene gas is released by calcium carbide in the presence of moisture, which might hasten ripening-related processes.

The use of calcium carbide can change the typical physicochemical and biochemical properties of fruits, and commercial-grade material may contain hazardous contaminants, according to recent studies [1], [2].

The exterior look of artificially ripened fruit might resemble that of naturally ripened fruit, but the inside biochemical development might not happen in the same way. Moisture, colours, carbs, sugars, starch, organic compounds, hardness, and other quality-related components can all vary. Therefore, it is usually not possible to reliably distinguish between naturally ripened and artificially ripened fruits by visual inspection alone.Fruit composition can be accurately determined using conventional analytical methods; however, many of these procedures require laboratory equipment, chemical reagents, destructive sample preparation, and a significant amount of analysis time. Due to these constraints, quick and non-destructive methods that can recognise biochemical differences linked to various ripening conditions are required.

A promising non-destructive method for assessing the internal and exterior quality of agricultural goods is spectral analysis. Certain wavelengths are absorbed, reflected, or scattered when electromagnetic radiation interacts with fruit tissue, depending on the sample's chemical makeup and physical structure.

Thus, information on pigments, water, carbohydrates, proteins, and other organic components can be obtained through spectral measurements in the visible, near-infrared, and short-wave infrared regions. Specifically, molecular vibrations involving O–H, C–H, and N–H bonds—which are frequently linked to water, carbohydrates, sugars, and proteins—have an impact on near-infrared spectral responses [3].

Because of this, spectral analysis can be used to analyse metabolic changes that are sometimes invisible to the human eye. The usefulness of spectral and hyperspectral methods for assessing fruit age and quality has been shown in earlier research. Firmness, acidity, pigment concentration, soluble solids content, and ripeness of various fruits and agricultural goods have all been evaluated using hyperspectral techniques [4]–[7].

Firmness and soluble solids content can be predicted using optical and multispectral measures, according to studies on apples [4]. Hyperspectral techniques have also been used to assess maturity-related biochemical characteristics in tomatoes [7], assess the ripeness of kiwifruit [6], and estimate the internal characteristics and ripening development of mangoes [5]. These results verify that quantifiable differences in spectral response are produced by metabolic changes that take place during ripening.

Despite these advancements, a large number of current studies mostly concentrate on recognising artificially ripened fruits based on outward appearance, categorising maturity stages, or forecasting specific quality metrics. The direct comparison of the full-range spectral fingerprints of naturally and artificially ripened fruits, as well as the interpretation of the main spectral variations in relation to underlying biochemical elements, have received very little attention. Additionally, a comparative multi-fruit study encompassing bananas, apples, and mangos can offer a more comprehensive knowledge of whether artificial ripening results in observable spectrum changes among fruits with various physical and physiological features.

Therefore, the current work uses non-imaging spectral reflectance analysis to examine biochemical differences between naturally and artificially ripened apples. An ASD FieldSpec 4 spectroradiometer was used to obtain the spectral signatures of apple, mango, and banana samples spanning the wavelength range of 350–2500 nm. To improve minor spectrum fluctuations and lower noise, preprocessing was applied to the acquired spectral data. The wavelength regions exhibiting notable changes between naturally ripened and artificially ripened samples were then identified using comparative analysis. Spectral areas linked to pigments, water and moisture, sugars, starch, and other organic substances received special attention.

This study's primary contribution is the identification and biochemical explanation of wavelength-specific differences linked to artificial and natural fruit ripening. The study looks at the spectral regions that contribute to the observed variations in ripening conditions rather than depending solely on overall categorisation accuracy. A foundation for comprehending how variations in fruit composition affect spectral behaviour is provided by the identified spectral markers. It is anticipated that the results will aid in the creation of quick, non-destructive, and data-driven methods for evaluating fruit quality and differentiating fruits exposed to various ripening circumstances.

II. LITERATURE REVIEW

Traditionally, destructive physicochemical measures and visual inspection have been used to evaluate fruit ripeness and quality. However, the complicated molecular changes that take place during ripening might not always be apparent from the fruit's outward look. Fruit tissue's reaction to electromagnetic radiation is affected by changes in colours, moisture, starch, sugars, acidity, firmness, and other organic substances. As a result, spectroscopy and hyperspectral methods have been studied more and more as quick and non-destructive ways to assess fruit quality and ripening conditions.

Lu [8] looked into the use of multispectral imaging to forecast apple fruit's firmness and soluble solids content. The study showed that information about internal quality qualities might be obtained from spectral and scattering properties. The findings provided a crucial foundation for estimating physicochemical characteristics that are directly related to the ripening process of fruit using optical measures. Additionally, the study supported the use of spectral methods for non-destructive fruit quality assessment by showing how changes in interior composition can affect observable spectral responses.

Ullah et al. [9] used fluorescence spectroscopy to study the non-invasive evaluation of mango ripening. Mango pulp and peel were measured spectrally at various stages of ripening. Significant spectral peaks were found at 540, 680, 705, and 740 nm, indicating that physiological and pigment-related changes during mango ripening result in detectable spectral differences.

Without requiring harmful testing, the study demonstrated that spectroscopy could differentiate between unripe, somewhat ripe, and fully ripe mangoes. These results are especially important since they show how wavelength-specific spectral behaviour and metabolic changes during ripening are related.

Using spectral bands of 380–1030 nm and 874–1734 nm, Guo et al. [10] used hyperspectral imaging to assess the freshness of strawberries. The study employed principal component analysis to determine significant wavelengths and categorised strawberries into unripe, mid-ripe, and ripe stages. To enhance the assessment of ripeness, spectral and textural characteristics were integrated. The findings demonstrated that wavelength selection can preserve information on ripening-induced physiological and physical changes while reducing data dimensionality. This work backs the identification of important spectral regions using feature extraction and dimensionality-reduction techniques.

Rungpichayapichet et al. [11] predicted the physicochemical characteristics of mango fruit using hyperspectral imaging. Regression analysis was used to examine spectral data in the visible and near-infrared range of 450–998 nm. The study produced geographic prediction maps that depicted the mango ripening process and projected hardness, total soluble solids, and titratable acidity. The results showed that spectral reflectance data can be used to estimate changes in internal biochemical characteristics. Because soluble solids and acidity are crucial biological markers that alter as fruit ripens, this work is very essential.

In order to assess strawberry ripeness in both field and lab settings, Gao et al. [12] looked into real-time hyperspectral imaging. Sequential feature selection was employed to find informative wavelengths in hyperspectral data collected spanning the 370–1015 nm wavelength range. The study showed that certain spectral characteristics might effectively differentiate between various stages of ripening. The findings also showed that a small number of important wavelengths might provide enough information for evaluating fruit ripeness, emphasising the significance of finding wavelength-specific spectral markers as opposed to using the entire spectral range without feature analysis.

Benelli et al. [13] used visible and near-infrared hyperspectral imaging in the 400–1000 nm region to assess the freshness of kiwifruit. As reference markers of ripeness, the amount of soluble solids and the firmness of the flesh were employed. The study showed that the quick and non-destructive evaluation of fruit maturity might be supported by spectral data. The authors demonstrated how useful correlations with internal physicochemical features can be found in hyperspectral data. These results support the idea that spectral response alterations might be used to indirectly identify structural and metabolic changes that occur during ripening.

Nguyen et al. [14] used hyperspectral imaging to study the assessment of achacha fruit maturity. To distinguish between distinct stages of fruit ripening, spectral data in the 400–780 nm region were examined. The study demonstrated that changes in fruit colour and pigment composition throughout ripening had a significant impact on observable spectrum fluctuations. The results verified that the spectrum distinction of ripening phases is greatly influenced by pigment synthesis and degradation, including modifications related to carotenoids and chlorophyll. The significance of the visible spectrum area for identifying metabolic alterations connected to fruit pigments is illustrated by this study.

A hyperspectral imaging method for determining the amount of soluble solids in mangoes was created by Tian et al. [15]. To determine internal quality, prediction models were created using spectral data gathered across the 400–1000 nm wavelength range. The study showed that spectral data may be successfully linked to soluble solids, which are directly linked to the buildup of sugar during fruit ripening. The findings show that spectrum analysis can be used to examine constituent-related variations in fruit samples because the conversion of starch into sugars is a significant metabolic transformation during ripening.

Renugadevi et al. [16] examined techniques for identifying artificially ripened fruits and emphasised the molecular distinctions between chemically induced and natural ripening. According to the study, artificial ripening agents like calcium carbide may affect fruit's physicochemical characteristics, including moisture, fibre, protein, and carbohydrates. The authors also talked about the shortcomings of traditional detection methods and the necessity of quick, non-destructive methods. Because it shows that artificial ripening may change the biochemical makeup of fruits, producing quantifiable traits that may be identified using spectral analysis, this work is directly pertinent to the distinction between naturally ripened and artificially ripened fruits.

The use of hyperspectral imaging and near-infrared spectroscopy for evaluating mango quality was examined by Chaudhary et al. [17]. The scientists clarified that chemical bonds like O–H, C–H, and N–H have an impact on near-infrared spectral responses, especially in the range of 700–2500 nm. Important fruit components, such as water, sugars, carbohydrates, and proteins, are linked to these molecular vibrations. The study highlighted the significance of preprocessing, wavelength selection, and chemometric modelling for precise quality assessment and showed that spectroscopy can provide details about the chemical makeup of fruit. Because they offer a biological foundation for understanding reflectance changes at certain wavelength regions, these observations are especially pertinent to full-range spectrum research.

The reviewed research show that fruit ripeness, firmness, soluble solids content, acidity, colours, and other quality criteria have all been satisfactorily assessed using spectroscopic and hyperspectral approaches. However, the majority of earlier studies have concentrated on forecasting a particular physicochemical characteristic, categorising traditional ripening stages, or examining a single fruit species within a constrained wavelength range. A comparative multi-fruit technique has been used in very few studies to examine the spectral differences between naturally ripened and artificially ripened fruits.

Additionally, a lot of current research focuses on categorisation performance without offering a thorough biochemical explanation of the wavelength areas causing the observed variations. Finding spectrum differences linked to changes in pigments, water and moisture, sugars, starch, and other organic ingredients under both artificial and natural ripening settings has received little study. Therefore, to comprehend how artificial ripening affects the spectral behaviour and underlying biochemical features of various fruits, a thorough analysis employing broad-range spectral data from 350 to 2500 nm is needed.

In order to close this gap, the current work uses spectral reflectance data collected across the 350–2500 nm wavelength range to compare naturally and artificially ripened apple, mango, and banana samples. In addition to detecting and analysing the wavelength regions linked to significant metabolic differences, the study focuses on distinguishing between the two ripening conditions. This method offers a more thorough comprehension of the connection between spectral response, biological makeup, and artificial ripening.

III. MATERIALS AND METHODS

A. Overview of the Proposed Methodology

The suggested study used spectral reflectance analysis to identify biochemical differences between naturally ripened and artificially ripened fruits. The three fruits that were chosen for the study were bananas, mangos, and apples.

Fruit sample preparation, spectral data collection, database building, spectral preprocessing, representative mean spectral signature computation, comparative spectral analysis, identification of important wavelength regions, and biochemical interpretation of the observed spectral variations comprised the overall methodology.

The following phases comprised the experimental procedure:

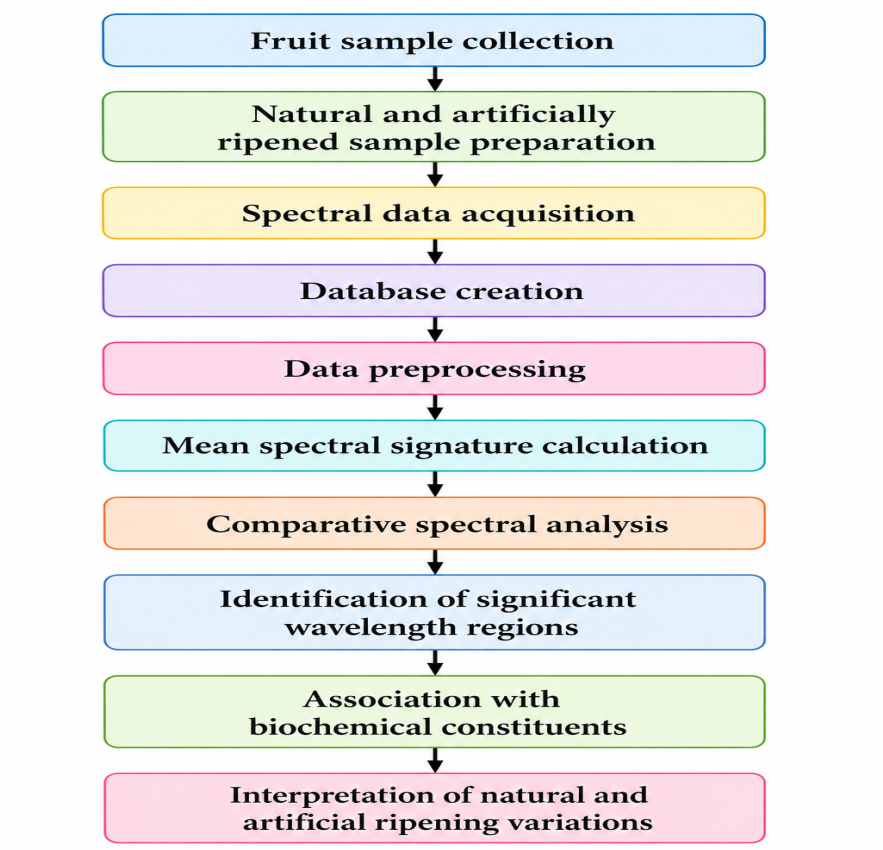

Fig 1: Proposed Methodology

The study focused on the complete spectral range from 350 to 2500 nm. This broad wavelength range enabled the analysis of spectral variations associated with visible pigments, internal tissue structure, water, moisture, sugars, carbohydrates, starch, and other organic compounds.

B. Fruit Sample Selection and Preparation

This study took into account three fruit categories: bananas, mangos, and apples. Spectral information from various ripening processes was obtained by including samples that represented both artificial and natural ripening settings. Measurements of the meat and peel were taken from banana samples. Thus, the spectral behaviour of both internal and external fruit tissues was represented in the banana database. Samples of apples and mangos were examined as entire fruits. To boost diversity within the database and improve the representativeness of the spectral analysis, a variety of fruit kinds were added. Local banana kinds ripened both chemically and naturally made up the banana samples. Dasheri, Totapari, Kesar, Mallika, Badam, and raw mango samples were all included in the mango database. Royal Gala, Irani, and Kashmiri apples were all included in the apple database. Because fruit variety, surface characteristics, pigment concentration, moisture, ripeness, and interior content may all naturally affect spectrum reflectance, it was crucial to include a variety. As a result, biological variability rather than measurements from a single fruit type was incorporated into the database.

C. Spectral Data Acquisition

An ASD FieldSpec 4 spectroradiometer was used to gather spectral data in the 350–2500 nm wavelength range. The device captures a continuous spectral signature that shows how electromagnetic radiation interacts with the fruit sample. A portion of the energy is absorbed and the remainder is deflected or scattered when incident radiation interacts with fruit tissue. The physical structure and biological makeup of the sample determine the final reflectance pattern. Thus, alterations in the spectral signature can be measured due to changes in pigments, water, moisture, carbohydrates, sugars, starch, and other organic elements. To account for inherent sample variability, many spectral measurements were obtained for each fruit group. For later investigation, the resulting spectral signatures were saved and arranged based on fruit type and ripening state.

D. Spectral Database Creation

A total of 710 spectral signatures were used in the present investigation. The complete database consisted of 180 banana spectral signatures, 330 mango spectral signatures, and 200 apple spectral signatures.

TABLE 1. SPECTRAL DATABASE USED IN THE PRESENT STUDY

Fruit	Total Spectral Signatures	Ripening Conditions	Part Analysed	Varieties Included
Banana	180	Natural and chemically ripened	Peel and flesh	Local banana varieties
Mango	330	Natural and chemically ripened	Whole fruit	Dasheri, Totapari, Kesar, Mallika, Badam, and raw mango
Apple	200	Natural and chemically ripened	Whole fruit	Kashmiri Apple, Irani Apple, and Royal Gala

The mango database was the largest, containing 330 spectral signatures from multiple varieties. The banana database contained180 signatures representing both peel and flesh, while the apple database consisted of 200 spectral signatures from three varieties. This multi-fruit database enabled a comparative investigation of spectral variations under natural and artificial ripening conditions.

E. Spectral Data Preprocessing

Although the raw spectral signatures may contain noise, baseline variations, scattering effects, and variations brought on by measuring settings, they also contain valuable biological information. Preprocessing was therefore carried out prior to the final spectral interpretation. Normalisation, second-derivative transformation, and noise reduction were all part of the preprocessing process.

Unwanted spectral signal variations were lessened by noise removal. Small spectrum differences between naturally occurring and artificially ripened samples were made more apparent by the second derivative's enhancement of modest absorption features and reduction of baseline effects. Normalisation decreased discrepancies resulting just from signal magnitude and brought the spectral values to a comparable scale. Spectral comparison, feature analysis, dimensionality reduction, clustering, and machine-learning classification were then applied to the produced data.

F. Computation of Mean Spectral Signatures

For every fruit type, many spectral signatures were available. If all of the individual spectra were shown at once, there would be much overlap, and it would be challenging to understand the main spectral pattern. As a result, each group's mean spectral signature was determined. The reflectance values of all spectral samples in the same class were combined together and divided by the total number of spectral signatures in that class for a given wavelength. The calculation for the mean reflectance was:

$$\text{Mean Reflectance}(\lambda) = [R_1(\lambda) + R_2(\lambda) + \ldots + R_n(\lambda)] / n$$

where n is the total number of spectral signatures in the relevant group, R is the reflectance value of a single spectral signature, and λ is the wavelength.At each wavelength between 350 and 2500 nm, the identical computation was carried out separately. For every fruit and ripening condition, this procedure produced a single representative mean spectral curve.Because fruit samples inherently exhibit biological variability, the mean was employed. Variations in fruit variety, surface texture, moisture content, ripeness, pigment concentration, and measuring location can all affect individual spectra. The group's overall spectral behaviour is highlighted and random sample-to-sample fluctuation is decreased by the mean spectral signature.Crucially, the mean was not computed as a single average number for the entire spectrum.Importantly, the mean was not calculated as a single average value for the complete spectrum. A separate mean value was calculated at every wavelength. Therefore, the original spectral pattern across the 350–2500 nm range was preserved.

G. Comparative Spectral Difference Analysis

Over the whole wavelength range, the representative mean spectral fingerprints of samples that were naturally and artificially ripened were compared. The investigation concentrated on areas where the mean spectral curves clearly separated or varied from one another. The following significant spectral areas were taken into account:

- Pigments: 400–699 nm • Internal tissue structure: 700–999 nm
- Water-related absorption at about 970 nm
- 1000–1300 nm: carbs and sugars
- Moisture-related absorption at about 1450 nm
- Water combination absorption at about 1900 nm
- 2100–2300 nm: sugars, starch, organic molecules, and associated components

The position of the spectral difference and the established correlation between wavelength regions and biological components served as the foundation for the interpretation. Finding each component's precise chemical concentration was not the goal. Rather, the analysis found wavelength ranges where the spectral behaviour of the naturally ripened and artificially ripened samples differed, and it explained these variations in terms of the corresponding biochemical components.

H. Identification of Biochemical Variations

Three steps were taken to identify biochemical variation. Initially, each fruit's mean spectral signatures from both naturally occurring and artificially ripened samples were plotted. Second, areas of wavelength where the two spectral patterns differed noticeably were found. Third, key fruit components such colours, water, moisture, sugars, carbohydrates, starch, and other organic substances were linked to specific wavelength ranges. Instead of just reporting visual differences between the curves, this method allowed the spectral differences to be interpreted in terms of biochemistry.

IV. RESULTS AND DISCUSSION

A. Mean Spectral Analysis of Natural and Artificially Ripened Fruits

The spectral signatures of banana, apple, and mango were analysed to determine whether natural and artificial ripening produced measurable changes in spectral behaviour. For each fruit group, the mean spectral response was calculated wavelength by wavelength to obtain a representative spectral signature.The mean spectral curves showed that the natural and artificially ripened samples did not exhibit identical spectral behaviour.

Differences were observed in the visible, near-infrared, and short-wave infrared regions. The magnitude of the variation was not uniform throughout the complete spectrum. Instead, certain wavelength regions showed stronger differences than others.

The most significant variations were seen in the 2100–2300 nm range, at 970 nm, 1450 nm, and 1900 nm. These areas are mostly linked to absorption of water, moisture, sugars, carbs, starch, and other organic molecules. Variations between 700 and 999 nm indicated changes in interior tissue structure, while additional variations in the visible range were linked to pigment alterations. These findings suggest that artificial ripening may affect fruit's biochemical and structural properties, changing its spectrum reflectance and absorption behaviour.

B. Spectral and Biochemical Variation in Banana

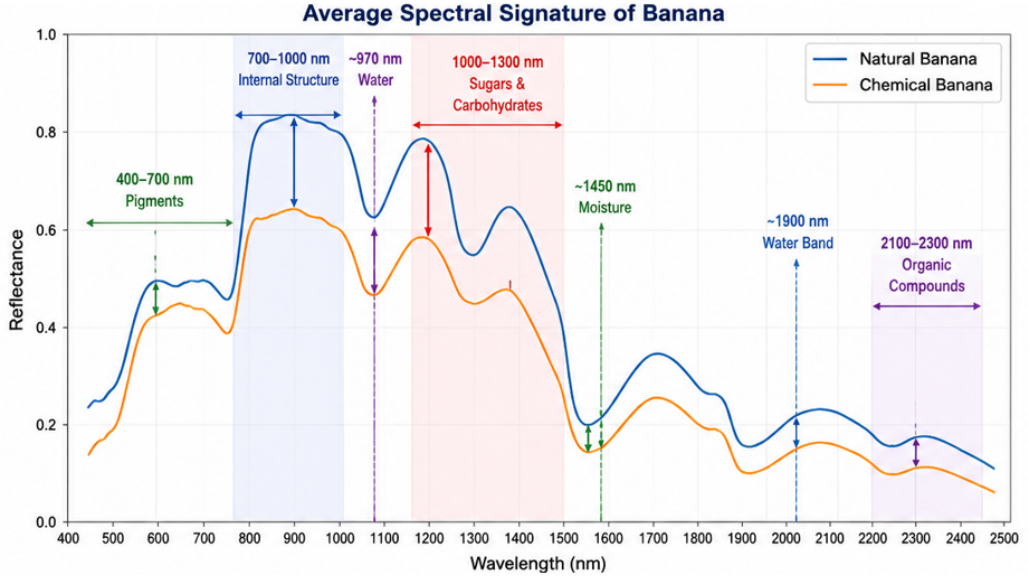

Fig. 2. Mean spectral signatures of naturally and chemically ripened banana samples.

Across a number of wavelength areas, the mean spectral signatures of banana samples demonstrated distinct differences between chemically ripened and natural conditions. The visible, near-infrared, and short-wave infrared regions were all affected by the spectral variations, which were not limited to a particular wavelength. Naturally ripened bananas displayed greater reflectance in the visible range of 400 to 699 nm. Fruit pigments are the main factor influencing this area. The observed variation suggests that during the ripening process, chlorophyll and carotenoid pigments are preserved and transformed differently. The natural banana samples also had increased reflectance between 700 and 999 nm. Light scattering and interior tissue structure have a significant impact on this area. The observed difference shows that naturally ripened samples have higher cell structure and tissue integrity preservation.

There was a moderate spectral difference at about 970 nm. Water-related absorption is linked to this wavelength. As a result, the variation shows that the two ripening conditions differ in terms of water distribution and water absorption properties. Between 1000 and 1300 nm, a significant spectral divergence was noted. This area is linked to absorption characteristics connected to sugars, starch, and carbohydrates. The spectrum fluctuation indicates variations in the transformation of carbohydrates between natural and artificial ripening since the ripening process entails the transformation of starch into soluble sugars. Near 1450 nm, a notable distinction was also noted. Moisture and O-H absorption are closely linked to this area. The fluctuation shows that the banana samples' moisture distribution varied.Another notable spectral difference was found about 1900 nm. This area shows variations in internal water and moisture properties and is a strong water combination absorption band. Moderate spectrum variations pertaining to organic molecules, sugars, starch, and other biological ingredients were seen in the 2100–2300 nm range. These findings show that rather than causing change at a single wavelength, chemical ripening affects several constituent-related spectral areas.

TABLE 2. SPECTRAL DIFFERENCE ANALYSIS OF BANANA

Wavelength Region (nm)	Associated Constituent	Observed Spectral Difference and Interpretation

Wavelength Region (nm)	Associated Constituent	Observed Spectral Difference and Interpretation
400–699	Pigments	Natural banana showed higher reflectance, indicating differences in chlorophyll and carotenoid preservation.
700–999	Internal structure	Higher reflectance in natural banana indicated stronger cell structure and tissue integrity.
970	Water	Moderate spectral difference indicated changes in water absorption characteristics.
1000–1300	Sugars and carbohydrates	High spectral difference indicated variation in sugars, starch, and carbohydrate composition.
1450	Moisture	Significant difference indicated variation in moisture distribution.
1900	Water combination band	Significant difference was associated with internal water characteristics.
2100–2300	Organic compounds	Moderate difference was related to sugars, starch, and other organic constituents.

The banana results demonstrate that the strongest biochemical variations were associated with water, moisture, sugars, carbohydrates, and organic compounds. The mean spectral approach made these group-level differences easier to identify by reducing the overlap among individual spectral measurements.

C. Spectral and Biochemical Variation in Apple

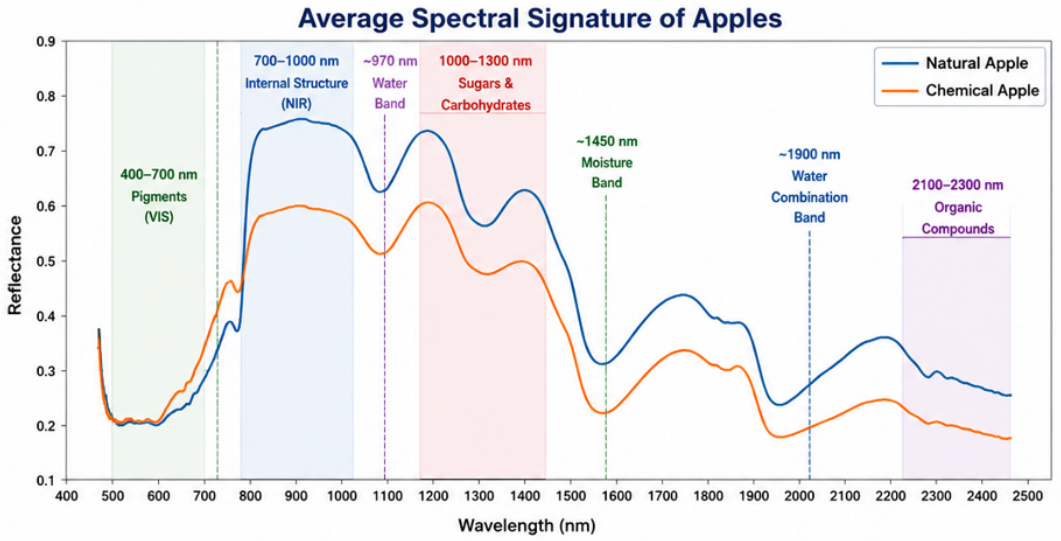

Fig. 3. Mean spectral signatures of naturally and artificially ripened apple samples.

Apple samples' mean spectral fingerprints clearly distinguished between artificial and natural ripening conditions. Like bananas, the detected alterations were spread throughout several wavelength regions, suggesting changes in the internal biochemical makeup as well as the exterior pigment properties. Chlorophyll and carotenoid pigments were linked to the spectrum fluctuation in the 400–699 nm range. The distinction shows that pigment development and degradation are influenced differentially by artificial and natural ripening. There were variations pertaining to interior tissue structure in the 700–999 nm range. Fruit tissue dispersion influences the spectral response in this area. Consequently, variations in cellular structure and tissue integrity are indicated by the observed variation.

Variations were linked to internal water distribution and water absorption at about 970 nm. Sugars, starch, and carbs varied in the 1000–1300 nm range, suggesting variations in the transformation of carbohydrates associated with ripening.

There was a noticeable spectral difference between the two environments in the moisture-related region at 1450 nm. In a similar vein, variations in internal moisture properties and water absorption behaviour were revealed by the strong water combination band about 1900 nm. Variations related to organic molecules, such as sugars, starch, and phenolic chemicals, were seen in the 2100–2300 nm range. The findings show that a number of biological traits are associated with the spectrum variations between naturally ripened and artificially ripened apples.

TABLE 3. SPECTRAL DIFFERENCE ANALYSIS OF APPLE

Wavelength Region (nm)	Associated Constituent	Interpretation
400–699	Pigments: chlorophyll and carotenoids	Indicates differences in pigment preservation and transformation.
700–999	Internal structure	Indicates differences in cell structure and tissue integrity.
970	Water band	Indicates variation in water absorption and distribution.
1000–1300	Sugars and carbohydrates	Suggests variation in sugars, starch, and carbohydrate composition.
1450	Moisture band	Indicates variation in moisture distribution and water absorption.
1900	Water combination band	Indicates differences in internal moisture characteristics.
2100–2300	Organic compounds	Indicates variation in sugars, starch, phenolic compounds, and related organic constituents.

The apple analysis confirms that natural and artificial ripening conditions can be differentiated through constituent-related spectral variations. The major differences were particularly relevant to pigment, water, moisture, carbohydrate, and organic-compound regions.

D. Spectral and Biochemical Variation in Mango

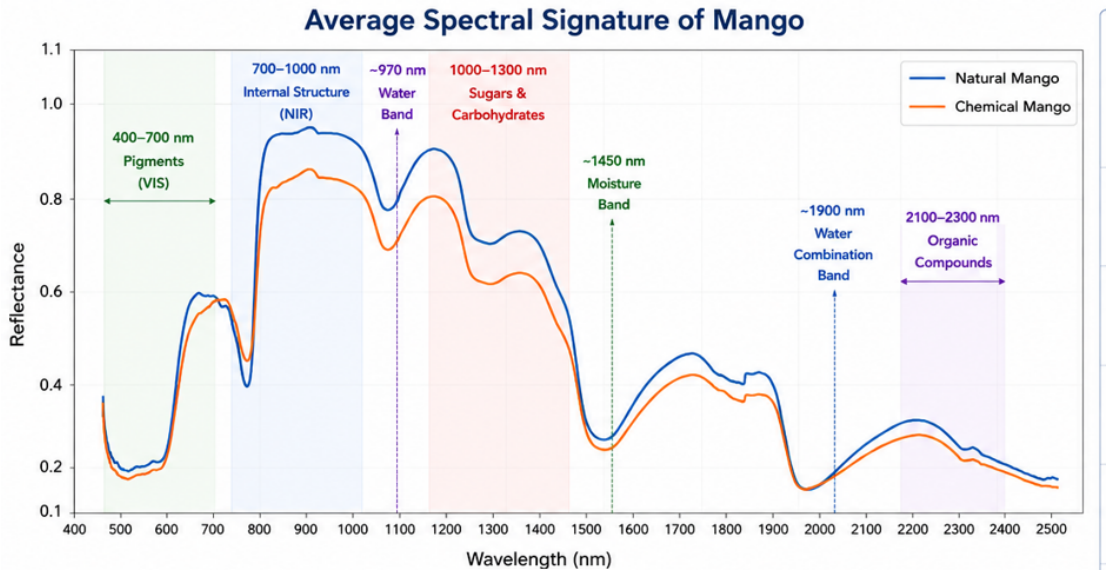

Fig. 4. Mean spectral signatures of naturally and artificially ripened mango samples.

Mango spectral fingerprints clearly distinguished between artificial and natural ripening conditions. A varied spectral database for examining ripening-related variation was made possible by the inclusion of Dasheri, Totapari, Kesar, Mallika, Badam, and raw mango samples. Chlorophyll and carotenoid pigments were linked to the spectral fluctuation in the visible spectrum between 400 and 699 nm. The observed discrepancy implies that pigment development and degradation are impacted differently by artificial and natural ripening conditions. Internal tissue structure was linked to the variance between 700 and 999 nm. Variations in tissue integrity and cell organization were revealed by the spectral behaviour.

Variations were linked to water absorption properties at about 970 nm. Variations pertaining to sugars, starch, and carbs were observed in the 1000–1300 nm range. Mango ripening causes significant changes in the growth of soluble sugar and the content of carbohydrates, which makes these variances significant. Spectral differences at 1450 nm revealed variations in water absorption and moisture distribution. The strong water combination band and internal moisture features were associated with fluctuation in the area around 1900 nm. Variations related to sugars, starch, phenolic compounds, and other organic components were observed in the 2100–2300 nm range. The findings show that artificial ripening affects several spectrum areas related to the metabolic makeup of mangos.

TABLE 4. SPECTRAL DIFFERENCE ANALYSIS OF MANGO

Wavelength Region (nm)	Associated Constituent	Interpretation
400–699	Pigments: chlorophyll and carotenoids	Indicates differences in pigment preservation and ripening-related pigment transformation.
700–999	Internal structure	Indicates variation in cell structure and tissue integrity.
970	Water band	Indicates differences in water absorption characteristics.
1000–1300	Sugars and carbohydrates	Indicates variation in sugars, starch, and carbohydrate composition.
1450	Moisture band	Indicates differences in moisture distribution and water absorption.
1900	Water combination band	Indicates differences in internal moisture and water absorption behaviour.
2100–2300	Organic compounds	Indicates variation in sugars, starch, phenolics, and other organic compounds.

The mango results verify that variations in mean spectral signatures can be used to identify ripening-related metabolic changes. Water, moisture, carbohydrates, sugars, pigments, and organic substances were linked to the most significant changes. The wavelength ranges of 970 nm, 1450 nm, 1900 nm, and 2100–2300 nm were found to be very significant in all three fruit groups, according to the comparison analysis. These areas are mostly associated with sugars, carbohydrates, starch, water, moisture, and other organic substances. These spectral regions are consistent among bananas, apples, and mangos, indicating that the observed variations are not limited to the outward look of a particular fruit variety. Rather, quantifiable alterations in constituent-related spectral behaviour are linked to artificial ripening.

E. Significance of Mean Spectral Analysis

The interpretation of the entire database required the application of mean spectral signatures. Plotting each of the 710 spectral signatures in the study would result in significant overlap. The mean spectrum preserved wavelength-dependent information while offering a representative pattern for each group. The mean computation made it simpler to see the main group-level spectral patterns and decreased random variation brought on by variations between individual fruit samples. Biological variation, however, was not regarded as a mistake. Fruits inherently differ in ripeness, variety, wetness, surface texture, and interior composition, so some overlap between naturally occurring and artificially ripened samples is expected. Consequently, the entire collection of individual spectrum samples was kept for statistical analysis and machine learning, while the mean spectral signature was utilised for visual and biochemical interpretation.

F. Major Findings

Four main conclusions were drawn from the spectrum study. First, samples of bananas, apples, and mangos that were naturally and artificially matured displayed distinct spectral behaviours. Second, rather of being evenly distributed throughout the whole 350–2500 nm range, the differences were wavelength-dependent. Third, areas related to pigments, internal tissue structure, water, moisture, sugars, carbohydrates, starch, phenolic compounds, and other organic components showed the biggest differences. Fourth, all three fruit types showed common spectrum alterations around 970 nm, 1450 nm, 1900 nm, and the 2100–2300 nm area. These results show that information on biochemical changes linked to various fruit ripening conditions can be obtained by broad-range spectral reflectance analysis.

V. CONCLUSION

This study used spectral reflectance analysis to examine biochemical differences between naturally occurring and artificially ripened bananas, mangos, and apples. 180 banana, 330 mango, and 200 apple spectra were among the 1,430 spectral signatures that were examined. An ASD FieldSpec 4 spectroradiometer was used to provide spectral observations over the wide wavelength range of 350–2500 nm. To increase the visibility and comparability of spectrum fluctuations, the obtained data were pre-processed using noise reduction, second-derivative transformation, and normalisation.

For both the naturally ripened and artificially ripened groups, mean spectral signatures were computed wavelength by wavelength. This method preserved the entire spectral pattern while reducing random sample-to-sample variance. For all three fruits, a comparison of the mean spectra revealed distinct changes between the two ripening regimes. These variations were focused in particular wavelength ranges linked to significant biological components rather than being evenly distributed over the entire spectral spectrum.

Variations linked to chlorophyll and carotenoid pigments were obvious in the 400–699 nm range, whereas variations in internal cell structure and tissue integrity were visible in the 700–999 nm range. Water absorption properties were linked to variations at 970 nm. Variations related to sugars, starch, and carbs were observed in the 1000–1300 nm range. Changes in moisture distribution and water-related absorption behaviour were suggested by notable fluctuations between 1450 and 1900 nm. Variations related to sugars, starch, phenolic compounds, and other organic components were observed in the 2100–2300 nm range.

The most noticeable and prevalent differences between bananas, mangoes, and apples were found in the spectral areas of 970, 1450, 1900, and 2200 nm. These results suggest that the ripening process is linked to quantifiable alterations in fruit's water, moisture, carbohydrates, sugars, pigments, and other organic components. Common constituent-related wavelength areas were found, despite the fact that the three fruit kinds' spectral differences differed in magnitude.

The findings show that spectral reflectance analysis offers valuable insights beyond fruit's outward look. Without harming the material, the suggested method makes it possible to identify and analyse internal biochemical changes. As a result, broad-range spectral analysis has great promise as a quick, non-destructive, and trustworthy method for evaluating fruit quality and distinguishing between naturally ripened and artificially ripened fruits. Future research can concentrate on creating reduced-wavelength sensing systems for useful and real-time fruit quality assessment as well as confirming the identified spectral regions using laboratory-based biochemical tests.

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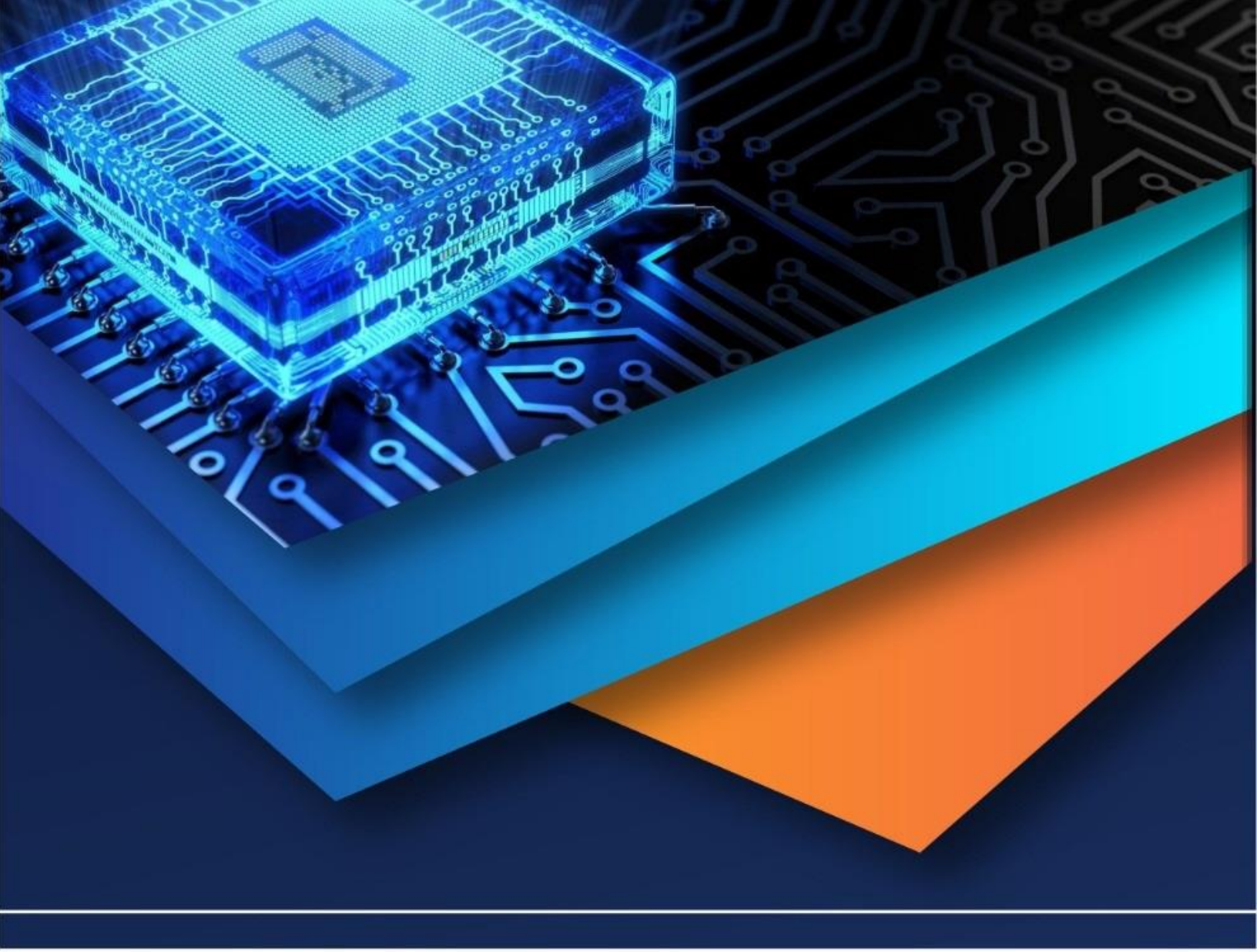

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